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MONTEREY, CALIFORNIA

NETWORK CENTRIC COMMUNICATIONS FOR

EXPEDITIONARY OR CARRIER STRIKE GROUPS

by

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14. ABSTRACT
The Department of Defense (DoD) utilizes the Global Information Grid (GIG) to provide the capability for deployed forces to obtain and share information with users dispersed worldwide. In the current US Naval communications architecture, ships within a strike group access services on the GIG predominantly through Satellite Communication (SATCOM) links. Typical SATCOM bandwidths found on small ships range from 256 – 512 kbps, while large ships have the capacity for 4 – 8 Mbps. While high bandwidth communications are available on large ships, small ships do not have the ability to leverage this bandwidth by dynamically selecting the most capable link available. Consequently, ships do not efficiently utilize the available bandwidth within the strike group limiting the ability for smaller ships to effectively gain access to services on the GIG. There is a need for a US Naval communications architecture that will create the ability for smaller ships to access the high bandwidth communications available on the large decks in order to obtain the most current information that the strike group may possess. Using this new architecture will allow all ships, resident in the strike group, to effectively access services on the GIG such as those provided by the Consolidated Afloat Network Enterprise System (CANES). In providing these services, platforms within the strike group will have the ability to share Service Based Architecture (SBA) information, leverage the most current data that is stored within the strike group and communicate with the external world through the most efficient and capable link. This research document proposes a system that will allow users on small and medium sized US Navy ships to gain access and utilize the much greater communications bandwidth that is available on the large Navy ships. The scope is restricted to investigating a means to provide disadvantaged users in a naval strike group to share the bandwidth from the larger ships by using technologies that are currently available. In performance of the research, a high level examination of the wireless distribution of bandwidth was conducted; however, a design solution was not developed. It was determined through the results of the simulation, that by effectively using the bandwidth and incorporating WiMAX on various ships throughout the fleet that the disadvantaged users' ability to obtain the most current situational awareness data in a timely manner would be greatly enhanced.

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ABSTRACT

Currently, US Naval ships do not efficiently utilize the available bandwidth within the strike group limiting the ability for smaller ships to effectively gain access to services on the GIG. In the current US Naval communications architecture, ships within a strike group access services on the Global Information Grid (GIG) predominantly through Satellite Communication (SATCOM) links. Typical SATCOM bandwidths found on small ships range from 256 – 512 kbps, while large ships have the capacity for 4 – 8 Mbps. While high bandwidth communications are available on large ships, small ships do not have the ability to leverage this bandwidth by dynamically selecting the most capable link available. There is a need for a US Naval communications architecture that will create the ability for smaller ships to access the high bandwidth communications available on the large decks in order to obtain the most current information that the strike group may possess. Using this new architecture will allow all ships, resident in the strike group, to effectively access services on the GIG such as those provided by the Consolidated Afloat Network Enterprise System (CANES). In providing these services, platforms within the strike group will have the ability to share Service Based Architecture (SBA) information, leverage the most current data that is stored within the strike group and communicate with the external world through the most efficient and capable link. The capstone team proposes a system that will allow users on small and medium sized US Navy ships to gain access and utilize the much greater communications bandwidth that is available on the large Navy ships. The research objective is to determine a means to provide disadvantaged users in a naval strike group to share the bandwidth from the larger ships by using technologies that are currently available. In performance of the research, a high level examination of the wireless distribution of bandwidth was conducted, however, a design solution was not developed. The capstone team determined, through the results of the simulation, that by effectively using the bandwidth and incorporating WiMAX on various ships throughout the fleet that the disadvantaged users' ability to obtain the most current situational awareness data in a timely manner would be greatly enhanced.

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Executive Summary

The current US naval communications architecture does not provide an effective means for disadvantaged users to access large amounts of resources via the Global Information Grid (GIG). Small and medium sized ships have limited satellite communications bandwidth (256 – 512 Kbps) which prevents them from accessing large volumes of data. Access to this data could increase their situational awareness or mission effectiveness. Since data transfers of these large data sets would impair the major communications link of the ship for extended periods of time, the commanding officer of the ship would be reluctant to use the SATCOM link for access to the GIG. Subsequently, as information richness within the GIG increases, the access limitations to the disadvantaged user will remain a major challenge.

Small and medium sized ships performing operations within a Carrier or Expeditionary strike group could benefit by utilizing excess SATCOM bandwidth that is available on large ships. The larger ships within the strike group have a much greater communications bandwidth capacity (4 - 8 Mbps) and may be able to provide some of this bandwidth to the disadvantaged users within the strike group. This bandwidth sharing between the ships would greatly reduce the duration of the data transfer, providing the disadvantaged user the ability to benefit from the GIG resources without disabling their own ships communications link for extended periods of time. The capability can be created by establishing a high bandwidth digital data link (mesh network) from ship to ship, through which the data would be passed. Using this construct would create the communications path through which data could be relayed through the large ship. Our report demonstrates that a medium sized ship utilizing only one-half of the large ships available bandwidth improves the delivery time of critical data by 87% over the amount of time that would be required if it used its own satellite link.

A total of three architectures with and simulation scenarios were designed to analyze the performance of ship-to-shore communications considering various ship platforms,

transmission mediums, and communication paths. The performance was evaluated based on file transfer times for Mine Warfare Environmental Decision Aid Library (MEDAL) products. MEDAL is an example of a DoD application that depends on enterprise services and provides mission critical data to a strike group. The three architecture models considered various communication links including SATCOM, Line of Sight (LOS) in the form of Digital Modular Radio (DMR), and LOS in the form of WiMAX.

Notable differences in the metrics occur when the communication architecture is changed, as is the case in the scenarios including LOS radios. The baseline scenario, the disadvantaged ships utilizing SATCOM to access large volumes of data, produces the worst case yielding a throughput of 0.49 Mbps and a transfer time of nearly 1 hour at 0.1% packet loss. The scenario using LOS DMR effectively uses the bandwidth available through the large deck. As a result, the throughput rises to 1.52 Mbps and the transfer time decreases to 18.2 minutes at a 0.1% packet loss. Furthermore, when increasing the data rate of the LOS link by deploying the WiMAX link and effectively using the available bandwidth through the large deck, throughputs rise significantly to 3.94 Mbps and transfer times shorten to just over 7 minutes. These results yield throughput improvements of almost 700% and transfer time improvements of 87% with respect to the baseline case. Although the modeling and simulation scenarios only reflect the use of LOS links in the form of DMR and WiMAX, the same trend can be applied to other LOS links possessing higher data rates.

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1 Introduction

The Department of Defense (DoD) utilizes the Global Information Grid (GIG) to provide the capability for deployed forces to obtain and share information with users dispersed worldwide. In the current US Naval communications architecture, ships within a strike group access services on the GIG predominantly through Satellite Communication (SATCOM) links. Typical SATCOM bandwidths found on small ships range from 256 – 512 kbps, whereas large ships have the capacity for 4 – 8 Mbps. While high bandwidth communications are available on large ships, current architectures do not allow smaller ships to benefit from the available bandwidth by dynamically selecting the most capable link available. Consequently, ships do not efficiently utilize the available bandwidth within the strike group limiting the ability for smaller ships to effectively gain access to services on the GIG.

There is a need for a US Naval communications architecture that will create the ability for smaller ships to access the high bandwidth communications available on the large ships in order to obtain the most current information that the strike group may possess. Using this new architecture will allow all ships, resident in the strike group, to effectively access services on the GIG such as those provided by the Consolidated Afloat Network Enterprise System (CANES). In providing these services, platforms within the strike group will have the ability to share Service Based Architecture (SBA) information, leverage the most current data that is stored within the strike group and communicate with the external world through the most efficient and capable link.

1.1 Background

In order to build a highly efficient and usable system for disadvantaged smaller US Naval vessels access to higher bandwidth from larger vessels, it is important to understand the information systems and architectures that are currently in use today. The following sections will present an example of the GIG and an associated set of services. The GIG provides users the capability to publish and subscribe to data repositories, which are shared commonly on the network. Users have the ability to query member databases to discover and retrieve information necessary to accomplish informed decisions. This gives an overview of how many ships access information and under what circumstances along with their challenges and limitations.

1.1.1 The Global Information Grid

The Global Information Grid (GIG) is a DoD program intended to provide users with the ability to access and disseminate information from locations dispersed worldwide. The National Security Agency (NSA) website (http://www.nsa.gov) describes the scope of the GIG in the following sentence:

"The GIG will be a net-centric system operating in a global context to provide processing, storage, management, and transport of information to support all Department of Defense (DoD), national security, and related Intelligence Community missions and functions - strategic, operational, tactical, and business - in war, in crisis, and in peace."

When the GIG was mentioned in a 2003 statement by Paul Wolfowitz, the Deputy Secretary of Defense, there was no government infrastructure to support the vision and the magnitude of the task was far reaching, (Biometrics Standards Working Group, 2011)The technologies, processes and policies necessary to provide GIG interoperability have been slowly tested and released by the Defense Information System Agency (DISA) over the past eight years. Capabilities now exist for users to leverage enterprise services, which are available in modern operating systems to discover and utilize information stored in remote servers located worldwide.

As shown in ***Figure 1***, (NSA, 2011), the GIG is intended to provide the framework for users to leverage information collected, maintained and shared by assets worldwide to provide timely access to data required for commanders to perform well-informed tactical decisions.

Figure 1–Global Information Grid OV-1

High-Level View of the Notional Physical Architecture of the GIG

Information is transmitted worldwide over communication links that range from Internet Protocol (IP) based radios and fiber optic cables to satellites; the GIG also provides an infrastructure to upload/download information.

Figure 2is a graphic taken from the DoD Global Information Grid Architectural Vision, Version 1, dated 2007, which shows the proposed GIG communications infrastructure. As can be seen from the links, data mainly flows from an asset to the satellite umbrella and there is no direct connectivity shown between the maritime assets.

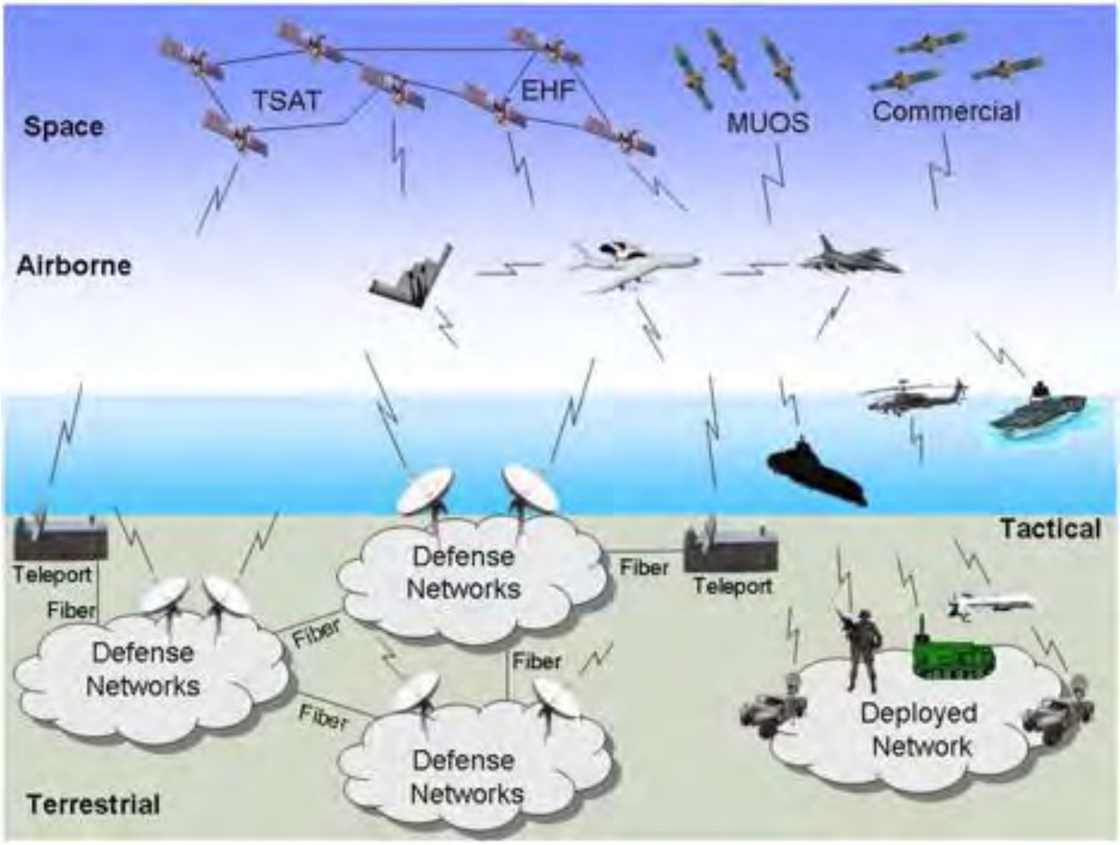

Figure 2 – Global Information Grid Communications Infrastructure

Pictorial Representation of Possible Communications Links which will Provide GIG Connectivity, DoD Global Information Grid Architectural Vision, Version 1, dated 2007

US Navy ships depend on these satellite links to gain access to data stored in remote locations. In addition, as capabilities emerge which support enterprise activities available through the GIG, these assets must rely on the radio frequency bandwidth available though their satellite antennas to upload and download information stored in remote locations. The bandwidth available to a specific class of ships is usually determined by the number and size of satellite antennas which can be supported onboard the platform. Therefore, as the size of the naval platform decreases, the bandwidth available for communications decreases leaving the smaller platforms at a severe disadvantage to access information in a timely manner. Typical scale factors between Radio Frequency (RF) bandwidth of large ships (aircraft carriers, amphibious carriers, etc) and medium size ships (cruisers, destroyers, Littoral Combat Ships (LCS), etc) can range from eight-to-one to sixteen-to-one. The smallest ship classes in the US Navy (patrol and mine countermeasure ships) usually have access to half the bandwidth provided to medium ships. Based on these factors, use of the GIG on small and medium sized ships to reap the benefits of the large volumes of data available through the GIG will be extremely taxing and may cause major disruptions in performance of communications assets on board the ship.

DISA also provides the Net-Centric Enterprise Services (NCES) for the GIG, which allows the user community to perform a variety of net-centric operations in addition to the ability to search, query and link to data stored worldwide. On board US Navy platforms, Enterprise Services will be hosted by the CANES program. CANES establishes a common hardware and software environment (scaled to the size of the host platform) intended to host all software programs running on the ship with the exception of weapons systems and systems associated with nuclear propulsion. In addition, CANES provides an enterprise service interface onboard the ship, which is identical to the GIG hosted services. ***Table 1*** shows the Enterprise Service overlap between the two programs.

Table 1 - Services provided by NCES and CANES

Portals [DKO/AKO, NEP/NMCP]	**Calendars [NCES, CANES]**
E-Mail [NCES, CANES]	**COOP [NCES, CANES]**
Security [NCES, CANES]	**Directory Service [NCES, CANES]**
Search [NCES, CANES]	**Social Networking [NCES, CANES]**
Metadata Generation [NCES, CANES]	**Chat [NCES, CANES]**

1.1.2 Mine Warfare Environmental Decision Aid Library Enterprise Architecture

An example of a DoD application that depends on enterprise services is the Mine Warfare Environmental Decision Aid Library Enterprise Architecture (MEDAL EA). The Mine Warfare Program Office (PMS-495) manages MEDAL EA, or MEDAL, which is part of the Program Executive Office for the Littoral Combat Ship (PEO-LCS). The MEDAL product is the Tactical Decision Aid (TDA) that is used by the US Navy and many of its allies to plan breaches or seeding of minefields located in the maritime environment.

Mine countermeasures is a complex task, performed by ships with sophisticated equipment that can detect, classify, reacquire and neutralize a mine threat. This is known as Intelligence Preparation of the Environment (IPE), which depends on the ability to access, display, employ, evaluate, update and fuse information stored in a variety of databases. Some of the products that are used for IPE are shown in ***Figure 3***.

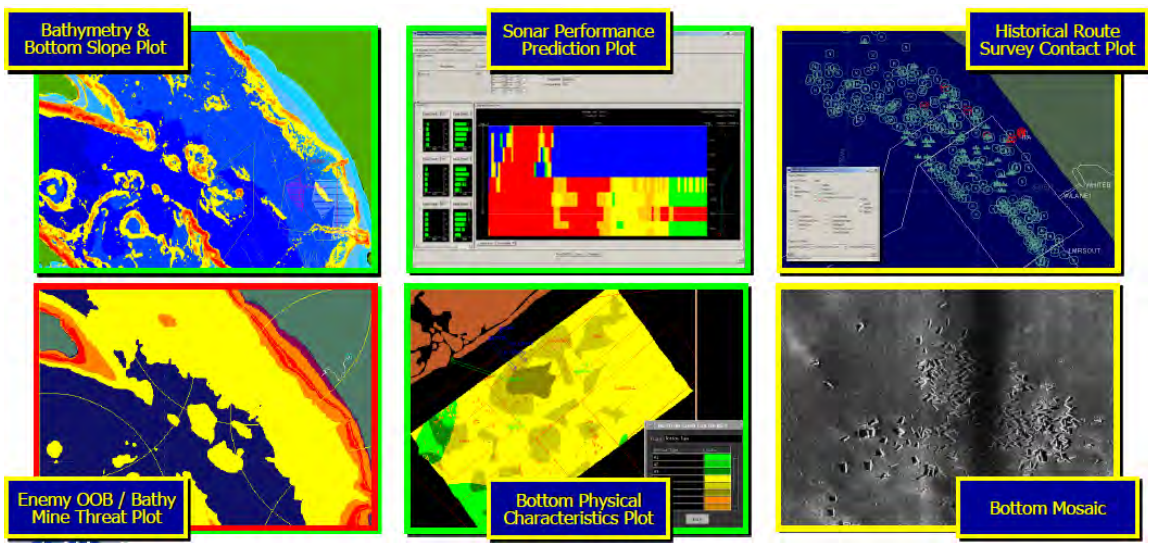

Figure 3 – Sample Intelligence Preparation of the Environment (IPE) Data Products

Representative Examples of MEDAL EA Data Products which Benefit From Fused Information, Source, PMS495 Mine Warfare Program Office, "MEDAL EA v1," Power Point presentation to Mr. J Ebken, Washington DC, August 3, 2011

The various data products provide users with specific views that help determine the type of equipment to deploy; hardware settings and recommended lane spacings to survey.

To perform a mine countermeasure mission, a naval asset is provided geographical coordinates, which define the boundaries of an area that must be cleared of hazards. Archival information for the operational area is then used to create a survey plan, which will be run by mine detection sensors. The MEDAL software then predicts the performance of the sensor, which will be used to execute the survey. The performance metric is the probability of detection for mine-like shapes predicted to be in the operational area. The performance is based on a number of parameters including bottom type, bottom clutter, salinity and temperature. Any errors in the values of the archived parameters can contribute to deviations in predicted performance for a given survey. For example, if the bottom type encountered is harder or softer than indicated in the archived data, the acoustic performance of the sensor may be compromised, which could yield a less accurate actual performance when compared to the predicted performance. This example is depicted in the sequence of images shown in ***Figure 4***

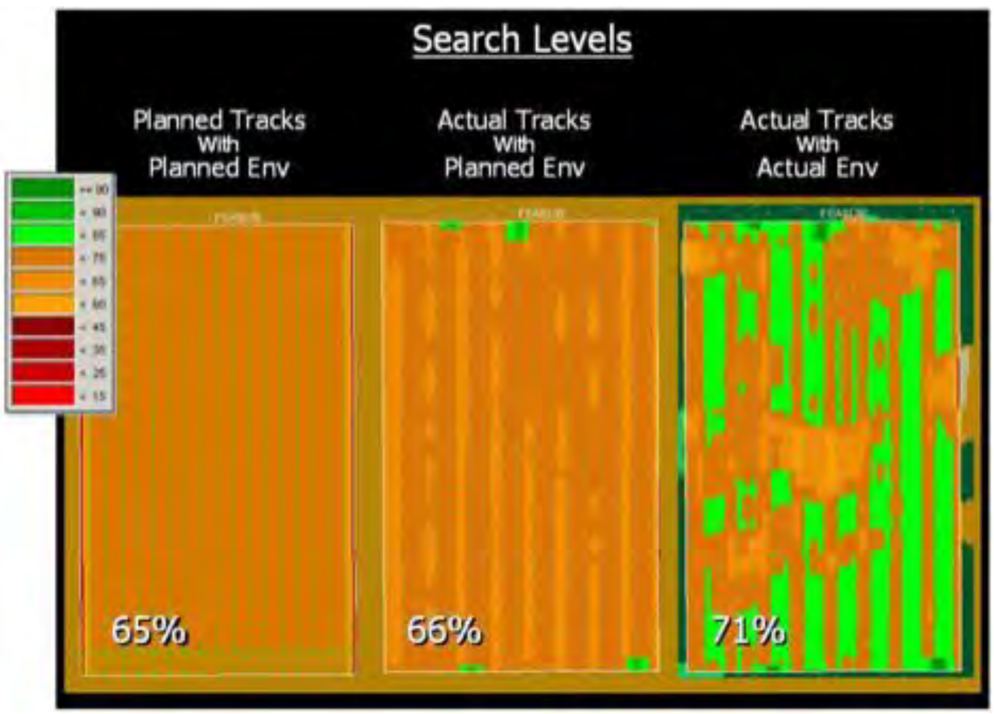

Figure 4 - Increased Performance with More Timely Data.

Graphical Depiction of Increased Detection Performance as Data is Collected
Source, PMS495 Mine Warfare Program Office "MEDAL EA v1," Power Point presentation to Mr. J Ebken, Washington DC, August 3, 2011

In the example given, the mine warfare asset updated the database used in MEDAL with information that was collected by a survey asset. The new information increased the probability of detection of representative objects in the given area from 66% to 71%.

Updated meteorological and hydrographic data that can affect the capabilities and performance of the sensors is also collected and archived by personnel in the Naval

Oceanographic Observatory (NAVOCEANO or NAVO), located in the Stennis Space Center in Mississippi. The archived data can be significant in size (~100s of Megabytes (MB)) and is readily available for users to perform the most concise operations. ***Table 2*** provides representative file sizes and frequency of update for data used to perform missions requiring access to MEDAL.

Table 2 - METOC Environmental Data Representative File Size and Frequency of Update
(PCTides = Navy Tide/Atmospheric Modeling System, xNCOM= High Resolution Naval Coastal Ocean Models)

MetOc Product Type	Sample Size	Anticipated Frequency
Forecast Products		
Water Current	Single Tau/Single Depth: PCTIDES: 25x25nm = 200 KB RNCOM: 600x900nm = 16 MB CNCOM: 200x200nm = 61 MB	Daily
	Multiple Tau/Multiple Depth: TBD	
Sea Surface Elevation	Single Tau: PCTIDES: 25x25nm = 8 MB RNCOM: 600x900nm = 23 MB CNCOM: 200x200nm = 98 MB	Daily
	Multiple Tau: TBD	
Bottom Current	Single Tau: TBD	Daily
	Multiple Tau: TBD	
Significant Wave Height	Single Tau: 200 KB	Daily
	Multiple Tau: TBD	
Historical Products		
Bathymetry	4 MB	Yearly (then refreshed during Ops w/ insitu)
Bottom Type	6 MB	Yearly (then refreshed during Ops w/ insitu)
HFEVA Sediment Type	8 MB	Yearly (then refreshed during Ops w/ insitu)
Roughness Category	150 KB	Yearly (then refreshed during Ops w/ insitu)
Clutter Category	10 KB	Yearly (then refreshed during Ops w/ insitu)
Percentage Mine Case Burial	150 KB	Yearly (then refreshed during Ops w/ insitu)
Climatological Products		
Optics	25 KB	Yearly
Forcing Mechanisms	10 KB	Yearly
Speed Statistics	10 KB	Yearly
Tidal Current	40 KB	Yearly
Surface Drift	10 KB	Yearly
Impact Surfaces		
Insitu Pershiability Map	50 KB	Daily / Weekly
Insitu Correlation Map	50 KB	Daily / Weekly
Currents Assessment	50 KB	Daily / Weekly
Optics Assessment	50 KB	Daily / Weekly
Forecast Confidence Map	50 KB	Daily / Weekly
Overhead Imagery	900 KB	Daily / Weekly

1.1.3 MINEnet Solution

In order for the fleet to capitalize on the operational benefits of current up-to-date information, it was necessary to develop a distribution mechanism that provides efficient access; the data must be accessed without having to perform complex setup and access procedures. Scientists and engineers associated with PMS-495 and NAVOCEANO have developed a distribution system shown in ***Figure 5***.

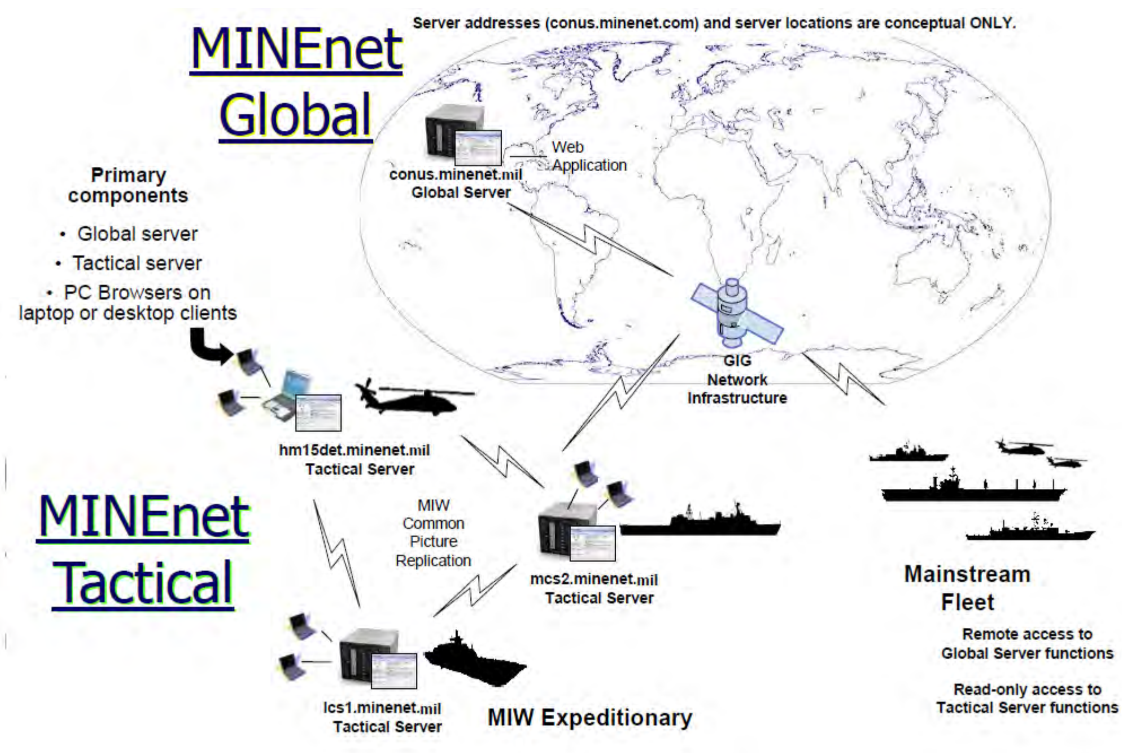

Figure 5 - MINEnet OV-1

High Level Graphic Showing Connectivity Between Mine Warfare Assets and Mine Warfare Databases, Source, PMS495 Mine Warfare Program Office, "MEDAL EA v1," Power Point presentation to Mr. J Ebken, Washington DC, August 3, 2011

MINEnet utilizes hardware contained in the GIG as well as Open Geospatial Consortium compliant web services to provide a publish-and-subscribe environment for qualified users to share information. Unfortunately, the major limitation to this technology is the ability for the disadvantaged tactical user, usually deployed on a small or medium sized ship, to retrieve necessary information without significantly hampering or completely saturating the limited communications bandwidth that is available onboard their ship. Given a block of data 200 MB in size and ideal connectivity at 512 kbps, it would take nearly 1 hour of the dedicated bandwidth for the platform. Any external communications over the dedicated satellite link would increase the download time. If the information were to be downloaded via a large ship (typical bandwidth allocations of 4 Mbps) the receive time under ideal conditions would be approximately 7 minutes. This increase in available bandwidth will allow users to access data previously unavailable during deployment, and it will provide a potential reduction in operational time on station due to increased performance prediction. The mine countermeasure community is dependent on timely and accurate mission data files to perform their missions effectively.

1.2 Scope and Assumptions

The scope of this research is to investigate a means to provide disadvantaged users in a naval strike group to share the bandwidth from the larger ships by using technologies that are currently available.

The research team is performing a high level examination of the wireless distribution of bandwidth but is not designing a solution. It is acknowledged that there are multiple shipboard enclaves (i.e. Top Secret/SCI) that aren't taken into account. Only the Secret enclave is acknowledged. Another assumption is that the transfer or the mission critical information is a high priority and policy is in effect to reflect this.

1.3 Project Team Organization and Systems Engineering Process

The organizational structure of the project's team is shown in ***Figure 6***. Roles and responsibilities are described in ***Table 3***.

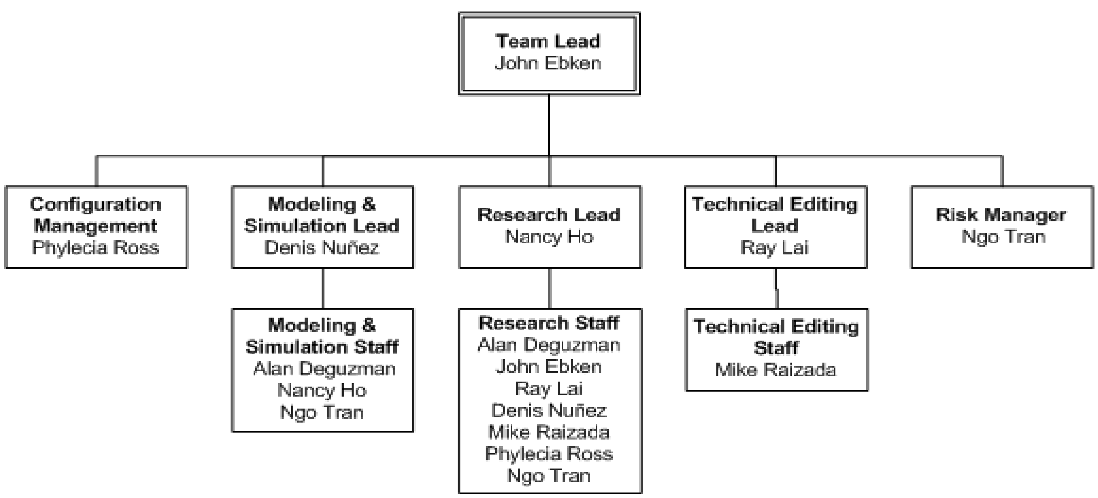

Figure 6 – Project Team Organizational Structure

Depicts the Capstone Research Team

Table 3 - Definition of Roles and Responsibilities

POSITION	ROLES/RESPONSIBILITIES
Team Lead	The Team Lead is ultimately responsible for all aspects of tasking and approves all work products. The Team Lead is the liaison with the NPS Capstone Advisors. The Team Lead coordinates meetings and conducts program reviews. The Team Lead will also provide guidance to all team members
Modeling and Simulation Lead	Manage all modeling and simulation tasking to include development of system architectures and network modeling, simulation, and analysis. The modeling and simulation lead will also participate in modeling architectures.
Modeling and Simulation Staff	Model and develop system architectures using Vitech CORE™. Model, simulate, and analyze communication systems and network architectures using tools such as ExtendSim7™ and Simulink™.
Research Lead	The Research Lead is responsible for directing research efforts as well as coordinating meetings with stakeholders and industry to gather data on current requirements and technologies. The lead will also participate in researching technologies and solutions.
Research Staff	The Research Staff will be responsible for conducting research and identifying potential solutions/alternatives.
Configuration Management Lead	The Configuration Management Lead is responsible for tracking and reporting configuration management matters to the Team Lead to include maintaining documents and project baselines.
Technical Editing Lead	The Technical Editing Lead is responsible for compiling and editing all deliverables.
Technical Editing Staff	The Technical Editing Staff will assist the Technical Editing Lead as required.
Risk Manager	The Risk Manager is responsible for reporting all cost, schedule, and performance risks to the Team Lead and advisors. All team members will participate in risk analysis and mitigation planning.

The Systems Engineering process model is a tailored version of INCOSE's SIMILAR process. The result is an iterative process in which a prior phase can be re-evaluated for refinement. While INCOSE's SIMILAR process can support projects up to the implementation of a system and the assessment of its performance, the scope of this project is limited to the recommendation of a solution to a problem by analyzing alternatives through modeling and simulation. The applicable phases to this project were determined as shown in the Systems Engineering process model chosen, ***Figure** 7*.

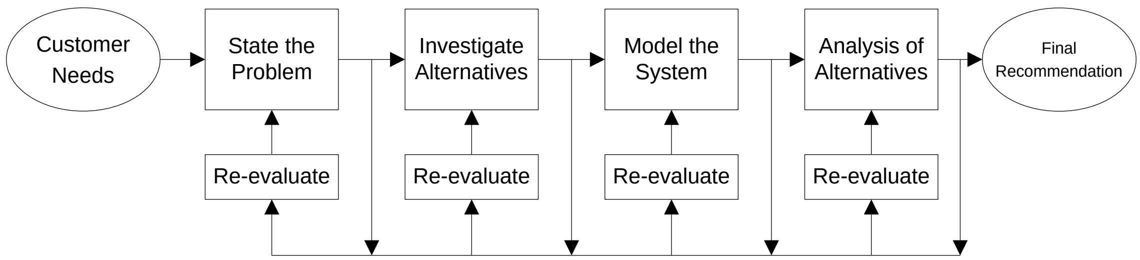

Figure 7 –SIMILAR Systems Engineering Process

Adopted Systems Engineering process applied to the research topic

2 Stakeholders Needs and Design Analysis

The SIMILAR process requires the customer needs to be gathered in order for the design analysis to be formalized. The following sections provide detail on the key stakeholders throughout the US Navy, an analysis of the requirements that resulted from stakeholder interviews, and an overview of the operational concept design.

2.1 Stakeholder Identification

The team reached out to the following stakeholders, as listed in ***Table 4***, via face-to-face interviews in addition to an extensive documentation review which included briefs, technical and operational manuals, policy instructions, and white papers. Through these research methods, the team was able to gather the current operational issues and needs of the US Navy Fleet. While scoping the problem for this research project, PMW 495 became a key stakeholder and helped the team develop a focus on network centric communications for mine countermeasure missions as an example for concept development.

Table 4 – Stakeholder Identification Table

Resource Sponsor	Acquisition Community	User Community
OPNAV N2/N6 Information Dominance	PEO C4I – PMW 160, PMW 170	Commander, United States Fleet Forces
OPNAV N852 Mine Warfare	PEO LCS – PMW 495	N/A
Office of Naval Research	N/A	N/A

2.2 Stakeholder Requirements Analysis

The inputs gathered from PMW 160 and PMW 170 allowed the team to understand the current naval networking and communications architecture. The research focused on identifying connectivity requirements for carrier and expeditionary strike groups as well as the communications capabilities among a diverse set of platforms to include submarines, surface ships, aircraft, and shore sites. Of these connectivity requirements, several applications and C4ISR functions were examined including command and control, battle management, sensor data dissemination, and situational awareness data. According to the Navy Tactics, Techniques, and Procedures, C4I Infrastructure, the Navy needs the following:

- “The ability to provide robust, reliable communication to all nodes, based on the varying information requirements and capabilities of those node.” (NTTP 6-02, pg 2-2)
- “The ability to provide reliable, accurate, and timely location, identity, and status information on all friendly forces, units, activities, and entities/individuals.” (NTTP 6-02, pg 2-2)
- “The ability to provide reliable, accurate, and timely location, identification, tracking, and engagement information on environmental, neutral and hostile elements, activities, events, sites, platforms, and individuals.” (NTTP 6-02, pg 2-2)

Through the stakeholder analysis, the team was able to identify the need for a communications architecture, which supports reliable and higher bandwidth links, especially for time sensitive applications. Given that varying platforms and applications present unique challenges, the scope of the project was narrowed to focus on the connectivity and communications requirements for mine warfare missions. The team interviewed engineers at the Office of Naval Research (ONR) and PMS 495 and further bounded the scope of the research to identifying communications technologies and architectures to support the MEDAL EA.

2.3 Operational Concept Design

The system which needs to be developed will allow users on small and medium sized US Navy ships to gain access and utilize the much greater communications bandwidth that is available on the large Navy ships. This increased connectivity will provide many benefits including the ability for smaller ships to:

- Gain access to previously unattainable information which may be required to effectively perform their mission
- Disseminate large amounts of data which could be vital in planning or performing tactical exercises and missions
- Share information with all ships within range

An example OV-1 of the proposed segment, which was created for PMS-495, is shown in ***Figure 8***.

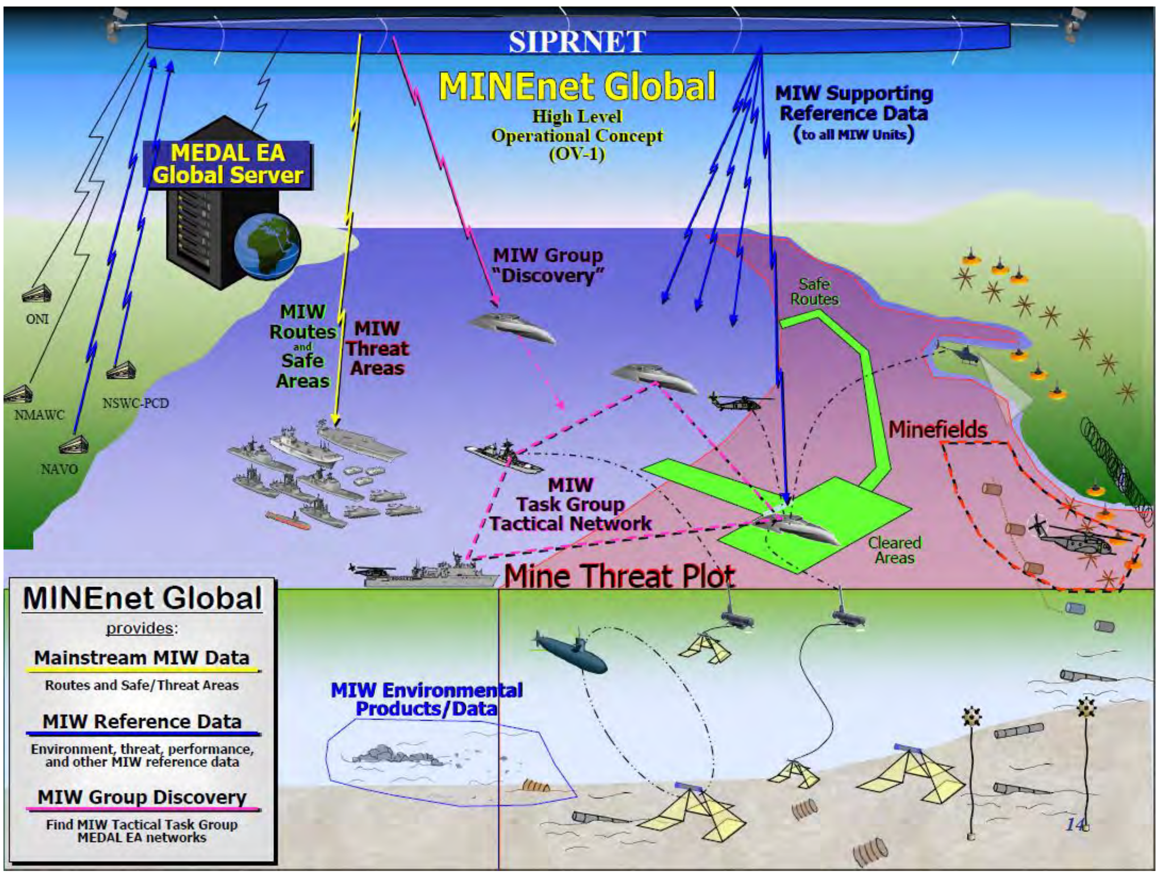

Figure 8 – Next Generation Automated Digital Network System

High Level Graphic Showing Connectivity Between Large Ships, Mine Warfare Assets and Mine Warfare Databases, Source, PMS495 Mine Warfare Program Office, "MEDAL EA v1," Power Point presentation to Mr. J Ebken, Washington DC, August 3, 2011

2.4 Initial Analysis and Requirements Summary

Based on the needs analysis, the team examined communications architectures to meet the following mine warfare mission operational requirements:

- Provide and maintain the connectivity required to execute Mine Warfare operations
- Tactical data synchronization between platforms
- Bandwidth efficient and reliable communications links for data intensive mine countermeasure operations

3 Research and Analysis

This section addresses the systems engineering design approach to the problem. The following subsections include the assumptions that had to be considered, constraints preventing optimal design, the hypothesized operational design, which is the design developed for optimal performance, and research analysis factors that are important factors in the overall design.

3.1 Assumptions and Constraints

The assumptions and constraints for the approach and each of the modeling scenarios are listed in Sections 4. They are summarized as follows:

- Total File Transfer Time = Transmission Delay + Propagation Delay + Queuing Delay.
- The links have a BER of 10^{-8}
- Routing delays are negligible when compared to the total file transfer time.
- The signal to noise ratio and power setting has been adjusted to obtain the appropriate data rates for each scenario.
- The LCS uses a WSC-6 antenna to establish a Super High Frequency (SHF) satellite link.
- The Carrier Vessel Nuclear (CVN) uses a WSC-8 antenna to establish an SHF satellite link.
- In order not to completely hamper the CVN, policy is in effect to use only 4.096 Mbps of the 8 Mbps available through the CVN's SATCOM link.
- The data rate of the LCS' SATCOM link is 512 kbps.
- The LOS link between the CVN and the LCS has a data rate of 1.544 Mbps.
- The WiMAX link between the CVN and the LCS has a data rate of 8 Mbps.

The assumptions were also checked against technical specifications and data provided within SPAWAR program briefs and consultations with SPAWAR subject matter experts.

A key constraint was the simulation the modeling tool, ExtendSim7™. There were some performance characteristics, such as the sliding window, that were not taken into account due to the limitations of the software. This constraint is discussed in further detail in Section 4.3.

3.2 Hypothesized Operational Design

During the concept design phase, the team hypothesized the system, Next Generation Automated Digital Network System (ADNS) that would provide the optimal bandwidth for a strike group. It was determined that the large deck ships, which have the higher performing resources to download data, could provide the primary means of accessing external sources, to the smaller ships, which are limited in communication resources. All ships within the strike group would communicate via narrowband terminals or WiMAXlinks for information sharing. ***Figure 9*** shows the high-level operational concept overview.

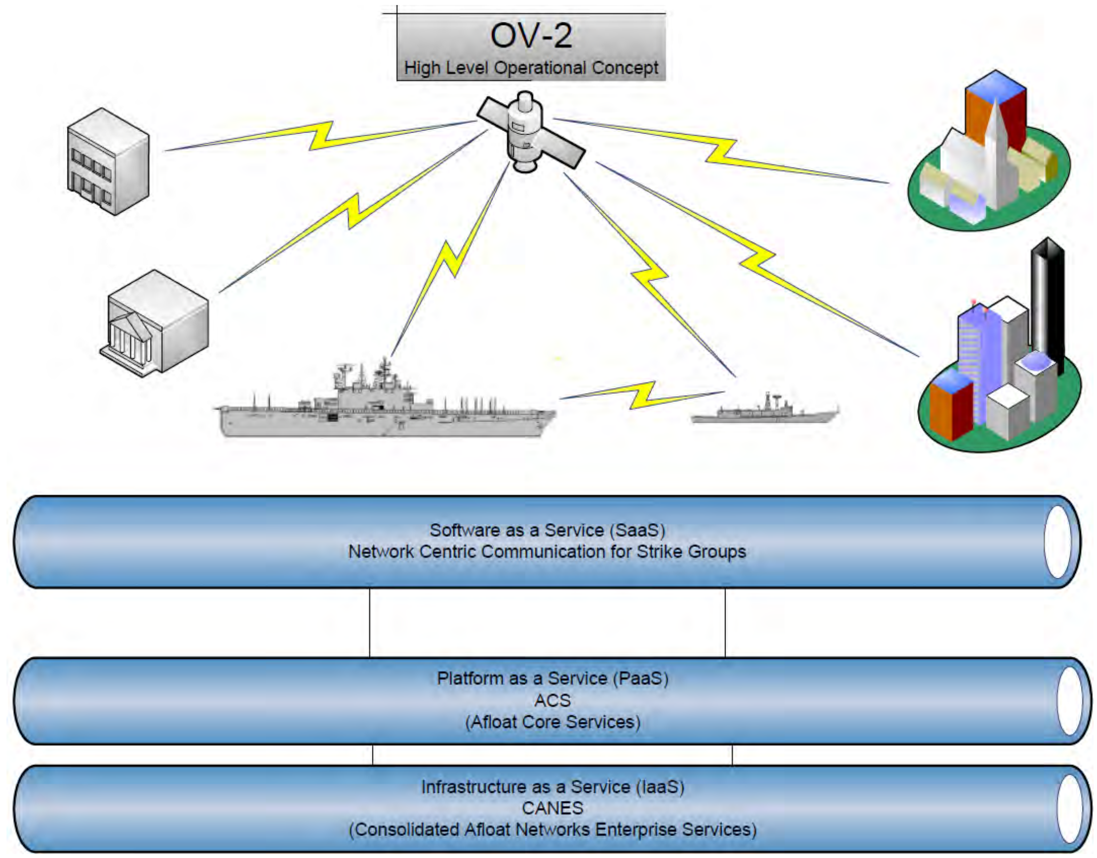

Figure 9 – Hypothesized Operational Design for Next Generation Automated Digital Network System (ADNS)

Depicts the connectivity and services that can be integrated

3.3 Research Analysis of Proposed Design

The research data that validates the proposed design is documented and demonstrated in Section 4. After running multiple simulations of various configurations, it was determined that the best system performance, from a data throughput perspective, is when the large deck ships connect to the GIG and communicate the data to the smaller ships using a WiMAX link.

3.3.1 Interference and Fading

The research team performed an analysis on available wireless technologies that could be adapted for use at sea and found that interference was a key issue. SPAWAR Systems Center Pacific has spent over a decade trying to address this issue as it supports the fleet.

One of the projects at SPAWAR is the Directional Ad hoc Networking Technology (DANTE). DANTE started in 2006 with the goal to resolve the tactical wireless network communications and interference problems by using focused directional antennas. The focused directional antennas were used to resolve interference with omni-directional antennas. Another key component of the DANTE technology was to make the ad-hoc wireless technology non-proprietary and radio agnostic.

One of the issues with wireless technologies used at sea is the issue of –beam squint," which means that many omni-directional antennas have a loss of beam steering due to the radiation pattern being spread over large instantaneous bandwidths. The DANTE project was able to address this issue by using a phased array with a Rotman lens beamformer, low noise power amplifiers, and an RF switch.

Potential interference on bandwidth frequencies for wireless communication can occur between some Commercial Off the Shelf (COTS) technologies. However, by adopting the DANTE solution, the risk can be mitigated. DANTE has already performed tests at sea with the unlicensed portion of the C-band (802.11a: 5.18-5.825 GHz) and has had no problems with any of the current frequency ranges used by the strike group. This was achieved with a directional antenna with an Effective Isotropic Radiated Power (EIRP) of 48dBm or 63W with a 17 dBi receive aperture and the low noise amplifiers, which set the noise figure to only 3-4dB. The standard coverage area by the DANTE antenna is 100 degrees in azimuth (+/5 50 degrees from broadside) with 8-switched beams having 12-17 degree half-power beam widths. Installing 4 DANTE antennas that will accommodate the Pitch and Roll of the ship in a turbulent sea can also have full 360-degree coverage. By adopting the DANTE antenna technology, interference from sea conditions and other frequency channels that the Navy currently employs can be completely eliminated. Our team recommends the use of the DANTE antennas as a potential solution as it has gone through three Trident Warrior at-sea tests successfully.

Interference that results from a point-to-point ad-hoc network over large areas can also be mitigated by the use of the DANTE system. DANTE can accommodate the collocation of antennas with multiple radios per antenna. This mitigates the current problem of excess RF cables that are needed to support the current naval standard of installing antennas on top of a mast. The DANTE software makes each of the antennas into a node to create tiered routing. This is ideal in dispersing the bandwidth efficiently from the large ships to the smaller ships in the strike group. A caveat to this is that LNA saturation can occur when ships are within 1 nautical mile of each other due to the high EIRP and fixed receive gain of the DANTE antennas.

Fading is a significant issue especially at sea. Multi-path fading caused by a sea-bounced signal can easily cause the signal strength to vary by 10-20dB over a short period of time" according to the tests conducted by the DANTE group. Due to this problem, the antenna to radio interface must be flexible enough to handle such a wide range. The DANTE group encountered the problem in the 2008 Trident Warrior test; they developed a new radio-controller interfacing and tracking technology to resolve this issue. By using software control of the receive antennas' LNA gains, the system could avoid the LNA saturation problems and the variability in fading over various distances at sea.

Interference from weather conditions such as rain can also be mitigated by the adoption of the new DANTE antennas. With a power transmitter on the ship operating between the two 802.11a bands (5.4-5.6 GHz) there was no signal loss during the 2008 Trident Warrior tests of the antenna.

3.3.2 Distance Between Ships in the Fleet

By deploying the DANTE technology, which can incorporate any of the fleet's existing radios, a range of 12 nautical miles can be provided. The DANTE technology currently supports up to 12 Mbps throughput point-to-point, or 4 Mbps over multiple nodes. DANTE provides lower throughput than WiMAX. However DANTE does not interfere with any of the fleet's current frequency ranges, thus overcoming most interference issues with sea deployment. The software to support the DANTE system has also been tested by the Spatially Aware Wireless Network (SPAWN), which was funded by the

Office of the Chief of Naval Operations (OPNAV). The current version of SPAWN used by DANTE can support data volumes up to 100+ Megabytes, without failure, when using high-powered satellite communications.

3.3.3 Encryption

WiMAX uses commercial encryption that may not meet fleet standards. However, the recommended DANTE antenna system has already solved the issue of security. The DANTE controllers can form Virtual Private Networks (VPN) and use tactical local area network encryptors to provide two layers of Internet Protocol (IP) encryption. This is fully interoperable with the Combined Enterprise Regional Information Exchange System (CENTRIXS) architecture by incorporating SPAWN.

4 Modeling and Simulation

The modeling and simulation section describes the approach used to examine performance characteristics of communication architectures supporting MEDAL applications. This includes a discussion of how ship-to-shore communications models were developed, simulation results, and an analysis of alternative communication architectures.

4.1 Model and Approach Baseline

The ExtendSim7™ software was used to develop architectures and perform time-based analysis of data communications for medium-sized ships supporting mine countermeasure missions. A total of three architectures with and simulation scenarios were designed to analyze the performance of ship-to-shore communications considering various ship platforms, transmission mediums, and communication paths. The Research and Analysis, Section 3.0, describes the research and analysis conducted which formed the basis for the communication models and scenarios. The models considered various communication links including SATCOM, Line of Sight (LOS) in the form of Digital Modular Radio (DMR), and LOS in the form of WiMAX. Performance was evaluated based on file transfer times for MEDAL products using the following equation:

$$T = \frac{L}{R} + \frac{d}{c} + Q_d$$

T: file transfer time in seconds
L: file size converted from bytes to bits
R: data rate in bits per second
d: distance
c: speed of light constant
Q_d: queuing delay

The simulations randomly vary the throughput requirements to represent various traffic profiles as described in Section 3. Of particular interest is the high operational tempo scenario in which MEDAL applications maintain the highest priority while ensuring quality of service for all other network applications. ***Figure 10*** provides a block diagram of the baseline communications architecture modeled in ExtendSim7™.

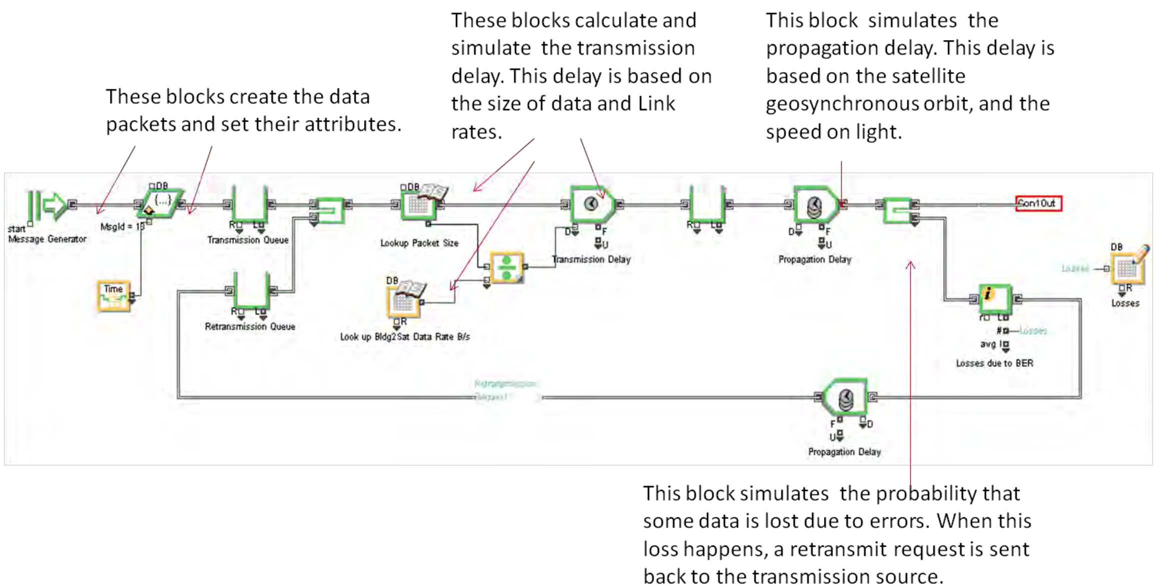

Figure 10 - Bldg2Sat Link Model in Block Form

4.2 Simulation Parameters

Parameter considerations and assumptions were obtained through PMW 160 and PMW 170 program briefs and interviews with SPAWAR Airborne-ADNS subject matter experts. ***Table 5*** lists MEDAL files that are typically downloaded. ***Table 6*** and ***Table 7***describe link parameters as well as other key model input parameters.

Table 5 – MEDAL File Set

Message ID	File Name	File Size (Megabytes)	File Size (Bytes)	Packets	Priority
1	Water Current PCTIDES	0.195	204473	134	1
2	Water Current RNCOM	16	16777216	11008	1
3	Water Current CNCOM	61	63963136	41970	1
4	Sea Surface Elevation PCTIDES	8	8388608	5504	1
5	Sea Surface Elevation RNCOM	23	24117248	15824	1
6	Sea Surface Elevation CNCOM	98	102760448	67428	1
7	Significant Wave Height	0.195	209715	137	1
8	In situ Perishability Map	0.048	52428	35	1
9	In situ Correlation Map	0.048	52428	35	1
10	Currents Assessment	0.048	52428	35	1
11	Optics Assessment	0.048	52428	35	1
12	Forecast Confidence Map	0.048	52428	35	1
13	Overhead Imagery	0.878	922746	605	1

Table 6 - Link Information

Scenario	Link type	Link Speeds (Mbps)
1	SHF SATCOM	0.5
2	SHF SATCOM	4.0
2	LOS (DMR)	1.544
3	SHF SATCOM	4.0
3	LOS (WiMAX)	8.0

Table 7 - Other Network Parameters

Parameter Name	Value
Geostationary Orbit	35,786 km
Speed of Light	$3x10^8$ m/s
Propagation Delay (SATCOM)	0.119s
Propagation Delay (LOS)	0.0001s
Packet Size	1524 Bytes
Packet Losses	0.1% and 5%

4.3 Limitation of Simulation Design Scenarios

The ExtendSim7™ tool was selected to explore the potential effects of various communications links at a high level and does not incorporate impediments such as rain attenuation, line of sight obstructions, or blockage zones. These environmental disturbances were simplified by obtaining a Bit Error Rate (BER) of 10^{-8} as referenced from a CBSP End-to-End Services Performance and Operational Data Report stating that a BER of less than 1 x 10^{-8} for all circuits for services delivered in the month of April 2011. Although BER is reflected at layer 1 of the Transmission Control Protocol / Internet Protocol (TCP/IP) stack, the model is only able to take in a value for the probability of packet loss. Since these occur at different layers of the TCP/IP stack, the

BER must be translated into packet loss. While bit errors can exist at the physical layer, Forward Error Correction (FEC) techniques can be used to resolve the bit errors in order to restore the fidelity of the packet. BER to packet loss translations also vary depending on the modulation scheme as well as other factors inherent the system. The Brand-Rex whitepaper titled, *The Impact of Bit Error Rate on LAN Throughput,* describes the correlation between BER and packet loss and makes several assumptions to show that a 10^{-7} BER corresponds to a 1% packet loss for big packets. Additionally, SPAWAR Airborne-ADNS subject matter experts were surveyed to collect realistic packet losses. Extrapolating data points from the whitepaper and obtaining information surveyed from subject matter experts, simulations were run using packet losses of 0.1% signifying an assumed normal environment, and 5% signifying a degraded environment in order to encompass a range of potential BER to packet loss translations.

Due to the limitations of the modeling tool, performance characteristics of various networking and communications protocols such as the sliding window were not taken into account. In the sliding window protocol, the rate at which packets are placed on the transmission medium is ramped up rapidly as long as acknowledgements are received to indicate a successful packet transfer. In the ExtendSim7™ model, acknowledgements are never sent back from the receiver at the ship to the sender at the shore; only retransmission requests are sent back in the event that a packet is lost. For further simplification, when a packet is lost, the retransmission request is sent and the data rate is held constant despite the additional congestion on the link from the retransmission request.

4.4 Simulation Scenarios

Data was collected and analyzed for four simulations with the first scenario considered as the baseline scenario. For the other scenarios, simulation results were analyzed and compared to the baseline to observe the impact of different architectures on the throughput and total file transfer time metrics. Additionally, simulation results were collected using packet losses of 0.1% and 5% for each scenarioin order to compare throughputs in a degraded environment versus a normal environment. Common model assumptions are listed below:

- Metrics collected focus on the total time taken to download the MEDAL files from the MEDAL EA Global Server.
- 142792 data packets of 1524 Bytes each represent the 13 MEDAL files.
- The links have a BER of 10^{-8}
- Total File Transfer Time = Transmission Delay + Propagation Delay + Queuing Delay.
- Throughput = Total Data Transferred / Total File Transfer Time
- Routing delays are negligible when compared to the total file transfer time.
- The MEDAL file set is top priority throughout the transfer.

4.4.1 Scenario 1: The Baseline Model – Current SATCOM Links

This scenario simulates the current communications architecture used for MEDAL applications. In this scenario, a medium-sized LCS obtains the most current situational awareness data from the MEDAL EA Global Server through a SATCOM link as shown in ***Figure 11***.

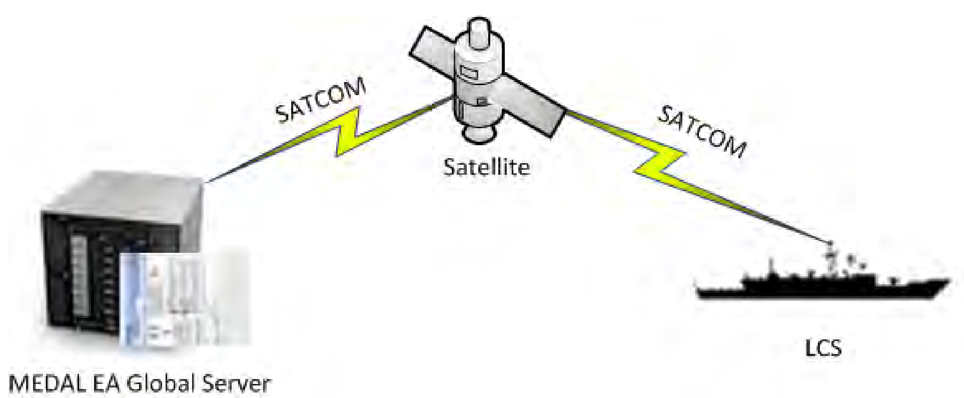

Figure 11 – Baseline: Current SATCOM Links

In addition to the common model assumptions in Section 4.4, the following assumptions are also made to this model:

- The LCS uses a WSC-6 antenna to establish a Super High Frequency (SHF) satellite link.

- The data rate of the SATCOM link is 512 kbps.

The results of this simulation are shown in ***Table 8*** below and again in ***Table 11*** of Section 4.5.

Table 8 – Scenario 1 Simulation Results

Metric	Throughput (Mbps)		Transfer Time (minutes)	
Packet Loss	0.1%	5%	0.1%	5%
Scenario 1	0.49	0.47	56.2	59.1

4.4.2 Scenario 2: Leveraging Carrier SATCOM and LOS Links (Ship-to-Ship)

Currently, the LCS is equipped with a DMR that can establish a LOS link with the CVN. However, the LCS is not currently configured to download the most current situational data through the CVN. This scenario depicts how the communication architecture could exist today if the LCS utilizes its LOS link to obtain the most current situational awareness data from a CVN, who downloads this information from the MEDAL EA Global Server through its SATCOM link. This is depicted in***Figure 12***.

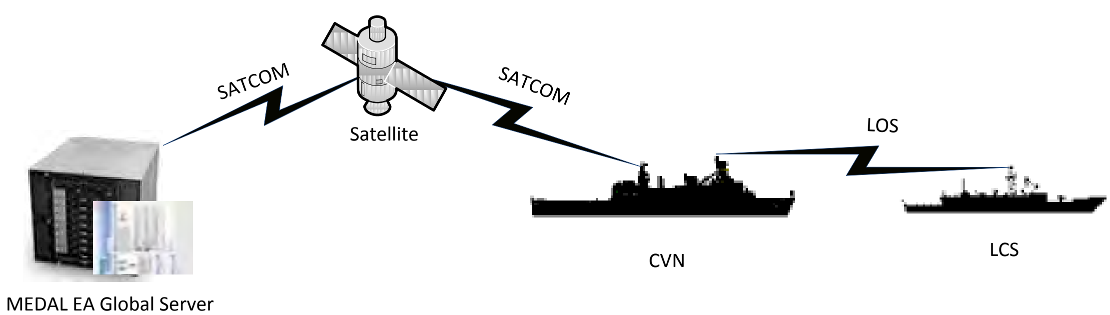

Figure 12 – Leveraging Carrier SATCOM and LOS Links (Ship-to-Ship)

In addition to the common model assumptions in Section 4.4, the following assumptions are also made to this model:

- The total file transfer time includes the time it takes for the CVN to download the MEDAL files as well as the download time from the CVN to the LCS.
- The CVN uses a WSC-8 antenna to establish an SHF satellite link.
- In order not to completely hamper the CVN, policy is in effect to use only 4.096 Mbps of the 8 Mbps available through the CVN's SATCOM link.
- The LCS uses a DMR to establish a LOS link with the CVN.
- The LOS link between the CVN and the LCS has a data rate of 1.544 Mbps.

The results of this simulation are shown in ***Table 9*** below and again in ***Table 11*** of Section 4.5. Throughput and transfer time improvements are compared with respect to the results of the baseline Scenario 1.

Table 9 – Scenario 2 Simulation Results

Metric	Throughput (Mbps)		Throughput Improvement		Transfer Time (minutes)		Transfer Time Improvement	
Packet Loss	0.1%	5%	0.1%	5%	0.1%	5%	0.1%	5%
Scenario 2	1.52	1.45	209%	209%	18.2	19.1	68%	68%

4.4.3 Scenario 3: Leveraging Carrier SATCOM and WiMAX Links (Ship-to-Ship)

This scenario considers the use of a WiMAX LOS link between the LCS and the CVN instead of the DMR LOS link established through DMR in Scenario 2. The LCS downloads the most current situational data using the WiMAX link to the CVN who downloads from the MEDAL EA Global Server through its SATCOM link. This scenario is illustrated in ***Figure 13***.

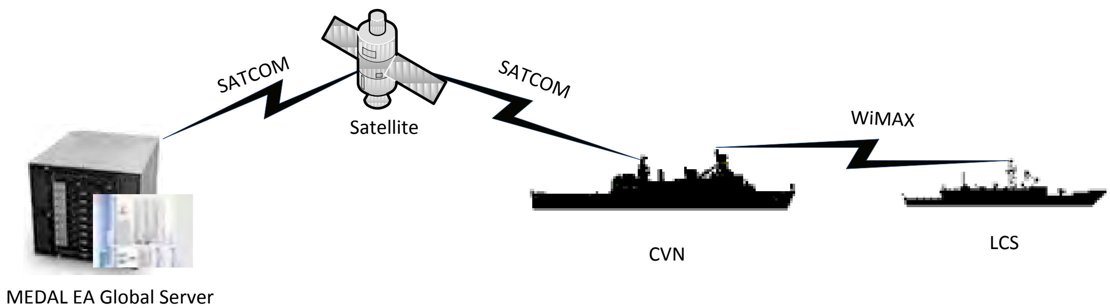

Figure 13 – Leveraging Carrier SATCOM and WiMAX Links (Ship-to-Ship)

In addition to the common model assumptions in Section 4.4, the following assumptions are also made to this model:

- The total file transfer time includes the time it takes for the CVN to download the MEDAL files as well as the download time from the CVN to the LCS.
- The CVN uses a WSC-8 antenna to establish an SHF satellite link.
- In order not to completely hamper the CVN, policy is in effect to use only 4.096 Mbps of the 8 Mbps available through the CVN's SATCOM link.
- The LCS downloads the MEDAL files through its WiMAX link with the CVN.
- The WiMAX link between the CVN and the LCS has a data rate of 8 Mbps.

The results of this simulation are shown in ***Table 10*** below and again in ***Table 11*** of Section 4.5. Throughput and transfer time improvements are compared with respect to the results of the baseline Scenario 1.

Table 10 – Scenario 3 Simulation Results

Metric	Throughput (Mbps)		Throughput Improvement		Transfer Time (minutes)		Transfer Time Improvement	
Packet Loss	0.1%	5%	0.1%	5%	0.1%	5%	0.1%	5%
Scenario 3	3.94	3.74	699%	699%	7.0	7.4	87%	87%

4.5 Simulation Results and Analysis

Table 11 shows the summary results, which includes the estimated throughput and transfer time for each scenario as well as the respective improvements from the architectures in scenarios 2 and 3. These results reflect an average of 50 simulation runs per scenario.

Table 11 - Summary of Simulation Results

Metric	Throughput (Mbps)		Throughput Improvement		Transfer Time (minutes)		Transfer Time Improvement	
Packet Loss	0.1%	5%	0.1%	5%	0.1%	5%	0.1%	5%
Scenario 1	0.49	0.47			56.2	59.1		
Scenario 2	1.52	1.45	209%	209%	18.2	19.1	68%	68%
Scenario 3	3.94	3.74	699%	699%	7.0	7.4	87%	87%

By referring to the times referenced in Table 11 and relating them to the accomplishment of a mine clearance mission, it is evident that the satellite communications for the medium sized ship receiving the data from NAVOCEANO can be severely impacted while accessing the GIG. In Scenario 1, the ship performing the MCM mission would require almost an hour to receive the most current files available from NAVOCEANO. During receipt of these files, the MCM ship would be unable to utilize the SATCOM link to communicate with other ships in the strike group since all of the bandwidth would be dedicated to the receipt of files from NAVOCEANO. It is extremely unlikely that a commander would eliminate his main communications link with the world for this extended period of time. Scenario 2 provides a communications link to NAVOCEANO through a portion of the large deck ships satellite link. During this 20 minute period of time, the medium-sized ship would be able to utilize the full bandwidth of their satellite communications link, while the large deck ship would suffer a minor reduction in their SATCOM throughput. The benefit to the warfighter being that both ships in the strike group can maintain continuous satellite communications while the MCM ship retrieves recommended files from external sources. Scenario 3 provides a high bandwidth ship-to ship link between the medium sized ship and the large deck ship. In this scenario, the reduction in bandwidth to the large deck ship would last less than 8 minutes. Again, all ships in the strike group would be able to maintain continuous satellite communications during the download, however, the carrier would only be limited to half of its bandwidth for a short period of time.

As discussed in section 4.3, limitations exist in the ExtendSim7™ model's inability to reflect link congestion and packet retransmissions in accordance with the sliding window protocol. However, while the results depicted in ***Table 11*** may not be entirely accurate, the overall trend is largely apparent. Notable differences in the metrics occur when the communication architecture is changed, as is the case in Scenarios 2 and 3. Scenario 1 produces the worst case yielding a throughput of 0.49 Mbps and a transfer time of nearly 1 hour at 0.1% packet loss. Scenario 2 effectively uses the bandwidth available through the large deck by utilizing its DMR LOS link. As a result, the throughput rises to 1.52 Mbps and the transfer time decreases to 18.2 minutes at a 0.1% packet loss.

Furthermore, when increasing the data rate of the LOS link by deploying the WiMAX link and effectively using the available bandwidth through the large deck, throughputs rise significantly to 3.94 Mbps and transfer times shorten to just over 7 minutes. These results yield throughput improvements of almost 700% and transfer time improvements of 87% with respect to the baseline case. Although the modeling and simulation scenarios only reflect the use of LOS links in the form of DMR and WiMAX, the same trend can be applied to other LOS links possessing higher data rates. As discussed in Section 3, the DANTE system is a recommended LOS alternative that can also be used to accomplish similar throughput and transfer time as modeled in Scenario 3.

Given the results of the simulations run for the three different scenarios, it is clear that effectively using the bandwidth and incorporating WiMAX on various ships throughout the fleet will greatly enhance the disadvantaged users' ability to obtain the most current situational awareness data in a timely manner.

5 Risk Analysis and Assessment

The Naval SYSCOM Risk Management Policy was applied as guidance in the project risk management process for this research. The risk management approach includes compiling risk profiles, development of a risk database and completing a risk management strategy plan, which identifies potential cost, schedule or performance risks and mitigation plans.

5.1 Risk Methodology Overview

The risks are organized into the following risk categories:

- Architecture
- Hardware
- Policy
- Software
- Technical
- Technology

The technologies being assessed during research can vary significantly in maturity, therefore the approach followed is related to risk associated to Technology Readiness Levels (TRLs), *refer to* ***Appendix B***. Equipment and technologies with TRL 6 and above will be considered as a minimal risk and will not be identified in a risk matrix. Equipment and technologies rated TRL 5 and below will be identified on the Risk Report Matrix Guide, ***Figure 14****,* with scores based on their assessed maturity. Using this approach the proposed solutions can be additionally weighted with respect to the maturity of the technology incorporated in them.

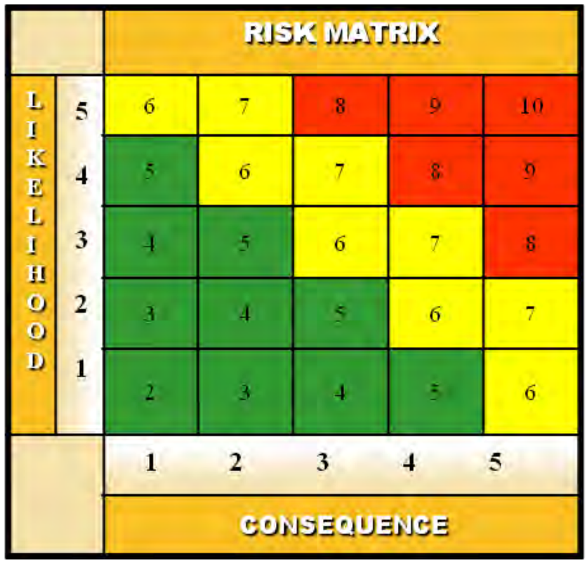

Figure 14 – Risk Report Matrix Guide

Table 12,provides the risks that the research team identified during this project. The risks have been assessed and the following sections describe the risk in detail, along with its likelihood of occurrence, the resulting consequences on system technical performance and a proposed mitigation strategy. ***Tables 12*** and ***13***, taken from the Risk Management Guide for DOD Acquisition, provide definitions of criteria used to determine risk.

Table 12 - DoD Level of Likelihoods Criteria

Level	Likelihood	Probability of Occurrence
1	Not Likely	~ 10%
2	Low Likelihood	~ 30%
3	Likely	~ 50%
4	Highly Likely	~ 70%
5	Near Certainty	~ 90%

Table 13- DOD Levels andTechnical Performance Consequence Criteria

Level	Technical Performance
1	Minimal/or no consequence to technical performance
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program
3	Moderate reduction in technical performance or supportability with limited impact on program objectives
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success
5	Severe degradation in technical performance; Cannot meet KPP or key technical/supportability threshold; will jeopardize program success

Eight specific risk areas have been identified that need to be addressed in order to implement ship-to-ship data sharing within either carrier or expeditionary strike groups. The individual risks are listed in ***Table 14***.

Table 14 – List of Identified Project Risks

Risk ID	Risk Factor
1	Architecture: Naval Communication Architecture does not support the RFLOS (Radio Frequency Line of Sight) for vessels within the CSGs (Carrier Strike Groups)and ESGs (Expeditionary Strike Groups)
2	Policy: Large vessels may be reluctant to give up bandwidth to other vessels
3	Technical Risk: Reliable high bandwidth communications between vessels are difficult to achieve (technical risk), since the alternative technologies (different radio frequencies, airborne relays) and networks have different levels of security classifications and compliance with the DoD Information Assurance Certification and Accreditation Process (DIACAP)
4	Technical Risk. Satellite Communications: All vessels do not have download managers, which sometimes causes a significant increase in the time to acquire data.
5	Technical Risk: Challenges of Transmitting over a range extension since the vessels do not have airborne relays to allow data be transmitted over a significant distance.
6	Technology: Applications of Wireless Technology limits to mobile WiMAX(802.11e) which has Interference and Inherent Limitations of Wireless Technologies. This includes but not limited to the interference at 12-km when using the same communications channels for both the WiMAX systems and satellites in C-Band
7	Hardware: Antenna, RF Front End on the Vessels compromises on Radio Coverage, Throughput, and/or Spectra Efficiency
8	Software: :Challenges of Mobile Wireless Network including Topologies, Protocols, Flow Control, and Traffic Route Planning

5.2 Identified Risks to Proposed Operational Design Concept

5.2.1 Naval Communication Architecture Risk and Mitigation Strategy

The existing Naval Communication Architecture (NCA) does not support digital Radio Frequency Line-of-Site (RFLOS) communications for vessels within the Strike Groups (Carrier and Expeditionary). The ships within the strike group transmit and receive digital data via satellite, even when the vessels are within the RFLOS in the VHF (30 -

300MHz) or UHF (300 MHz – 3GHz) ranges. Although a digital LOS route does exist,(DMR) radio, it is not utilized. Given that there is no current method to transmit and receive LOS digital data, the likelihood of occurrence is near certainty (5).
The consequences of this deficiency are severe degradation in technical performance (5). Network patches would need to be created to provide the data path between the ships.

Mitigation:
A new architecture must be developed to allow the ships to share digital information via LOS transmission paths. Another alternative would be to adopt a Wireless Technology Mobile Wi-MAX (802.11e) system within the strike group.

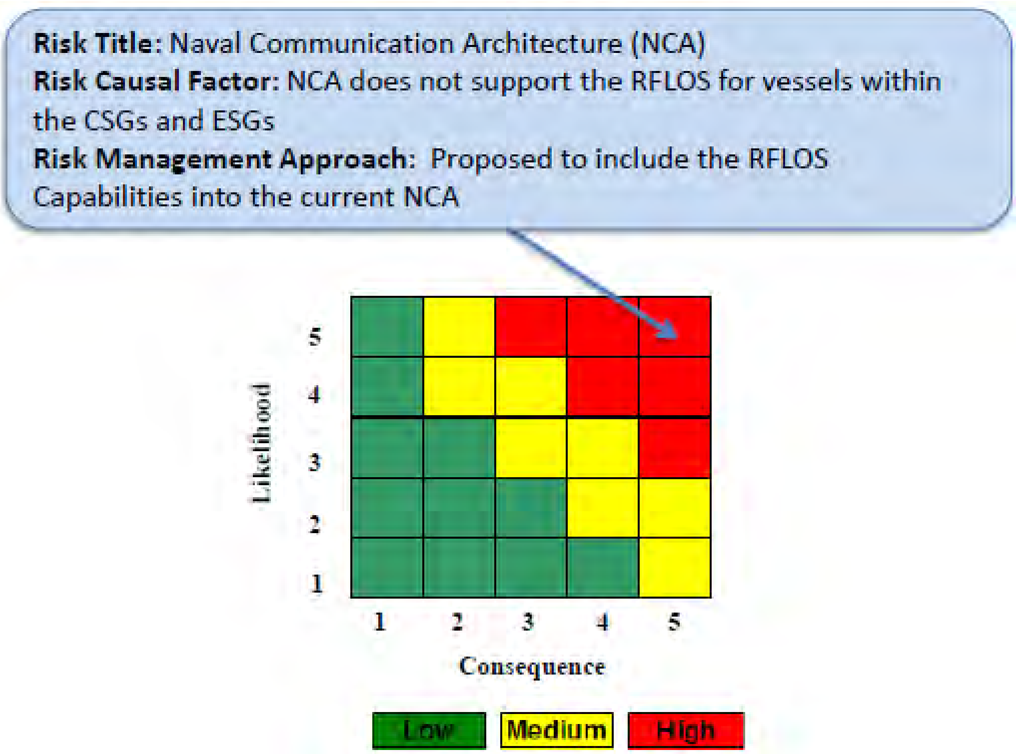

Figure 15 – Naval Communications Architecture Risk Matrix

5.2.2 Naval Communication Policy

Large vessels may be reluctant to give up bandwidth to other vessels within a strikegroup. Naval Communication Policy (NCP) does not address the ability for ships to share dynamic bandwidth among themselves. In addition, there is not a mechanism to automatically establish the carrier for the transmission based on the data flow's size and its priority, and no method to reallocate a link when the transmission is completed. Rules must be implemented which establish a protocol for ships within a strike group to request bandwidth from neighboring ships. These rules must contain metrics, which could be used by ships having excess communications bandwidth to determine if it is operationally viable to create the path for another user to use as a link. Again, the architecture is charting new territory, and an undefined communications policy is certain. Both the likelihood of occurrence of this deficiency and the consequences to the program must be rated high (5).

Mitigation:

To alleviate this risk, changes to existing naval communications policy must be developed. The adoption of these new policies would allow the disadvantaged ships the capability of gaining additional bandwidth from carriers and amphibious carriers to receive and disseminate data.

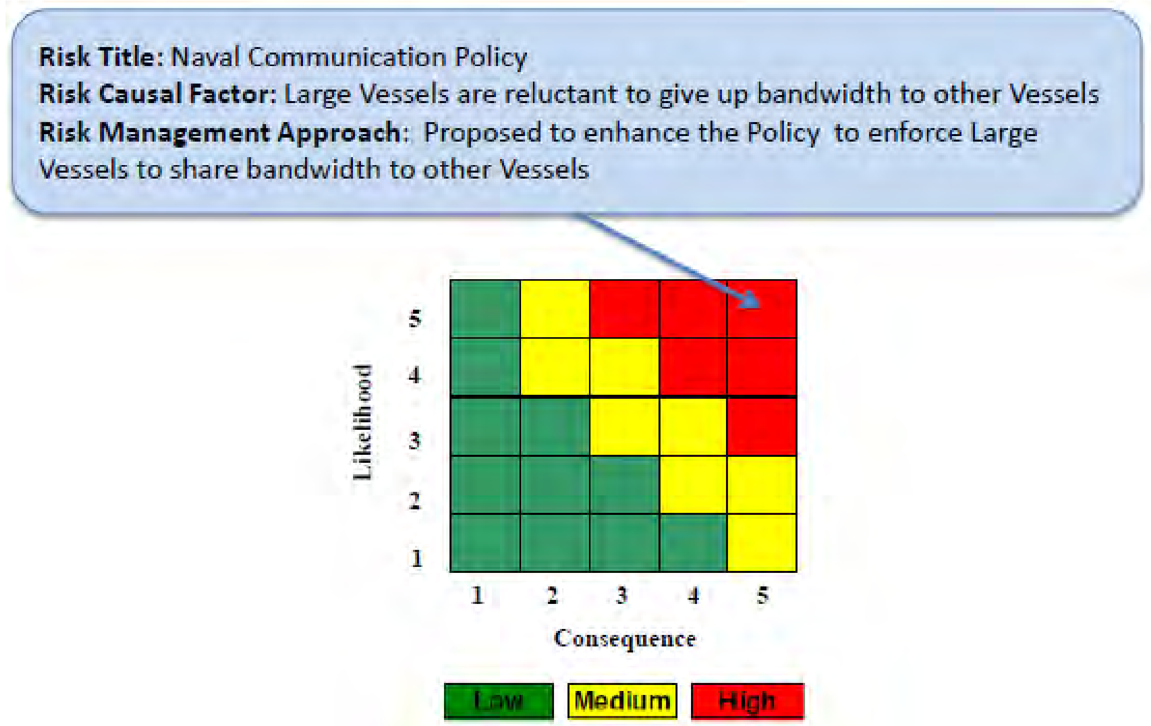

Figure 16 – Naval Communication Policy Risk Matrix

5.2.3 Reliable High Bandwidth Communications Risk and Mitigation Strategy

Reliable high bandwidth LOS communications between vessels is difficult to maintain, due to dynamic environmental conditions. In addition, networks must maintain different levels of security classifications and comply with the DIACAP (The DoD Information Assurance Certification and Accreditation Process), which increases overhead on communications. VHF and UHF LOS radio wave propagation in the maritime environment is dependent on the height and type of antenna being used to relay traffic. Omni-directional antennas provide a wide coverage area, but have reduced antenna gain to transmit the signal. Directional antennas provide increased gain, but must be aimed and stabilized to provide maximum performance. Given that a reliable, relatively high throughput data link is necessary to relay data between the small ship and the large ship, the team feels that the likelihood of encountering this risk is likely (3).The consequences associated with this risk will cause amoderate reduction in system performance (3); however, will not prevent the transfer of data.

Mitigation:

New technologies are becoming available to increase reliability of high bandwidth communications. The mitigation approach proposed is to research, enhance, or develop technologies that would have sufficient maturity to be realistically capable of eliminating the risk. Some of the technologies that were identified are based on wide band UHF radios and others are optical (laser) based. A few of the promising technologies that would address the communications reliability risk are described in the conclusions to this report.

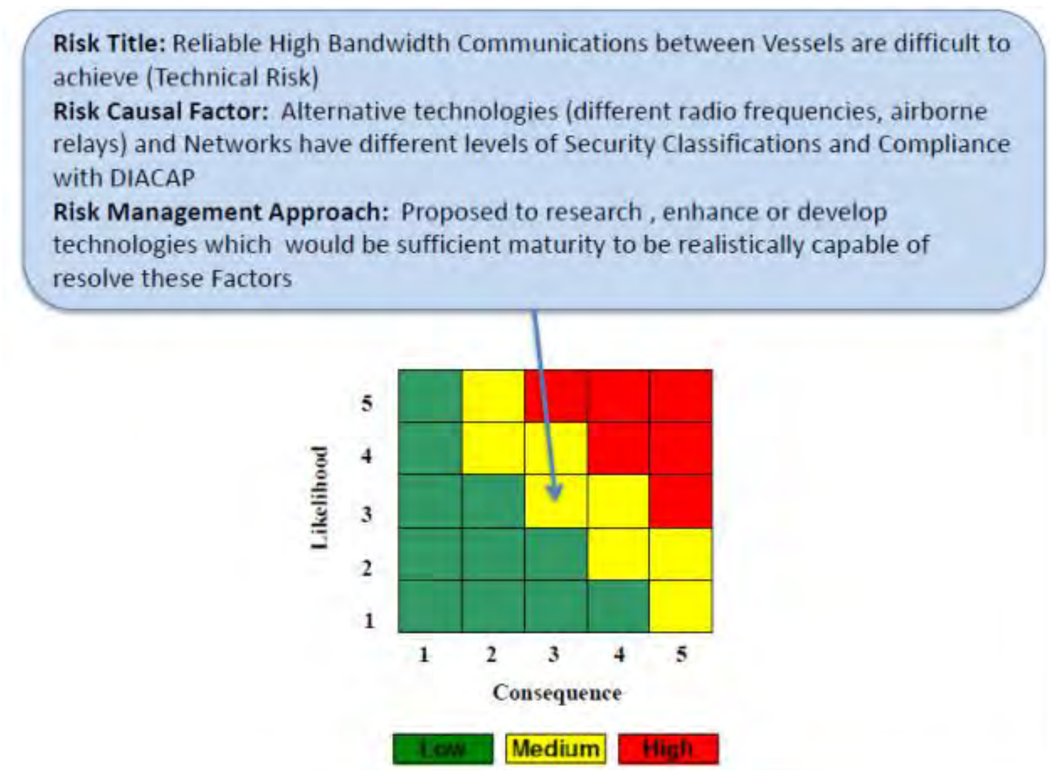

Figure 17 – Reliable High Bandwidth Communications Risk Matrix

5.2.4 Satellite Communications Risk and Mitigation Strategy

All satellite communications systems on Naval vessels do not contain a data download manager to handle data reception. If a download manager is not present, any disruption of the link during a transmission, anywhere in the download, will cause the system to request the entire message from the host server. An extreme example of this risk would be reception of a significantly large data file near its completion. An atmospheric anomaly causes a disruption in service, which drops a packet. The communications suite must request a re-transmission of the entire data set, thereby causing the message to take nearly twice as long to receive. The team was unable to quantify the number of Navy ships utilizing a download manager, but discussions with communications personnel indicate that there are few. The rated likelihood of occurrence is nearly certain (5). The consequences to the system design from this deficiency will cause a significant degradation in technical performance (4).

Mitigation:

Since download managers exist for satellite communications terminals, the most direct method of alleviating this risk would be to implement one on all ships transiting within a strike group. Research should be conducted to ensure that the download manager is optimized to handle communications typically conducted on naval platforms.

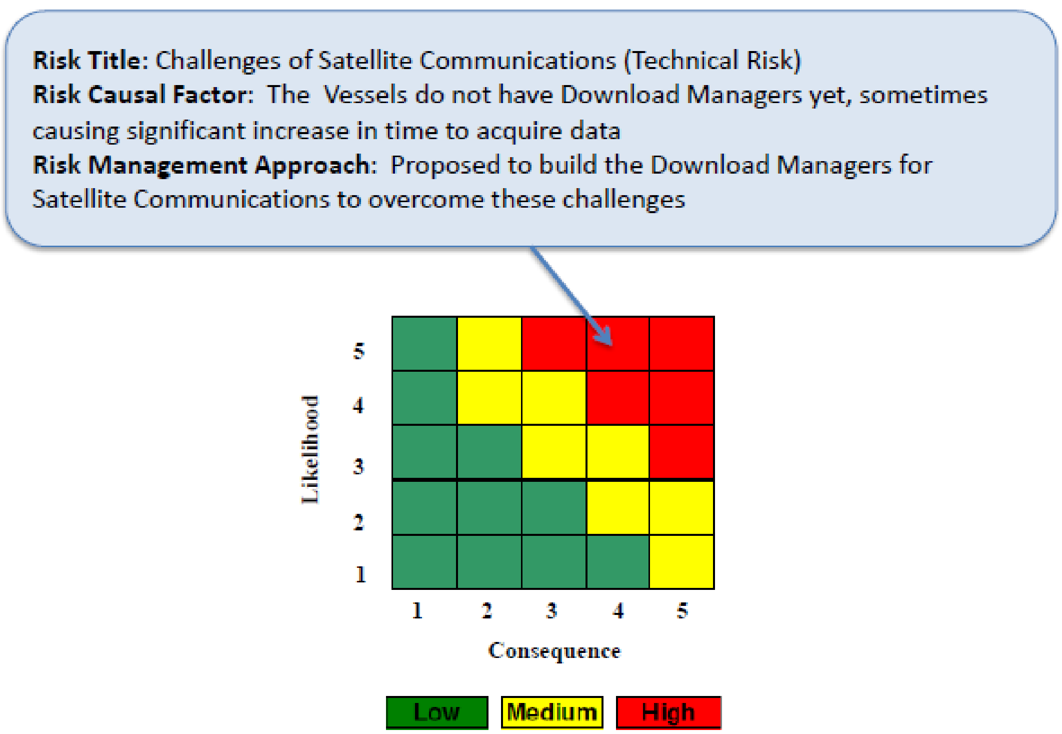

Figure 18 – Challenges of Satellite Communications Risk Matrix

5.2.5 Challenges of Transmitting Over a Range Extension Risk and Mitigation Strategy

Optimal conditions for reliable, high bandwidth LOS communications between ships are typically less than 50 nautical miles and the availability of airborne relays to augment LOS communications is minimal. Many successful experiments have been conducted using manned aircraft carrying relay nodes to extend LOS communications distances, however, unless a manned aircraft is scheduled to loiter in the vicinity of the strike group to perform other missions (i.e. reconnoiter, refueling, etc) the costs and additional personnel required to provide this capability are prohibitive. In the absence of aerial relays, members transiting within a strike group will be required to maintain this limited proximity to other members within the strike group in order to share satellite bandwidth. In some instances (i.e. mine warfare and ASW), this close proximity required between ships would put additional members of the strike group in danger. The likelihood of encountering this deficiency is near certainty(5) and the consequences to the design are significant degradation in technical performance (4).

Mitigation:

Continued studies need to be performed to assess implementation of an airborne relay mechanism that could be deployed as necessary to accomplish the communications range extension. ONR is currently evaluating Unmanned Aerial Vehicles (UAVs) and aerostats. Other methods could incorporate low cost expendables launched from a ship, to provide the communications link while airborne and then self-destruct. Several of the airborne communications packages, in development, are discussed in the conclusions section of this document.

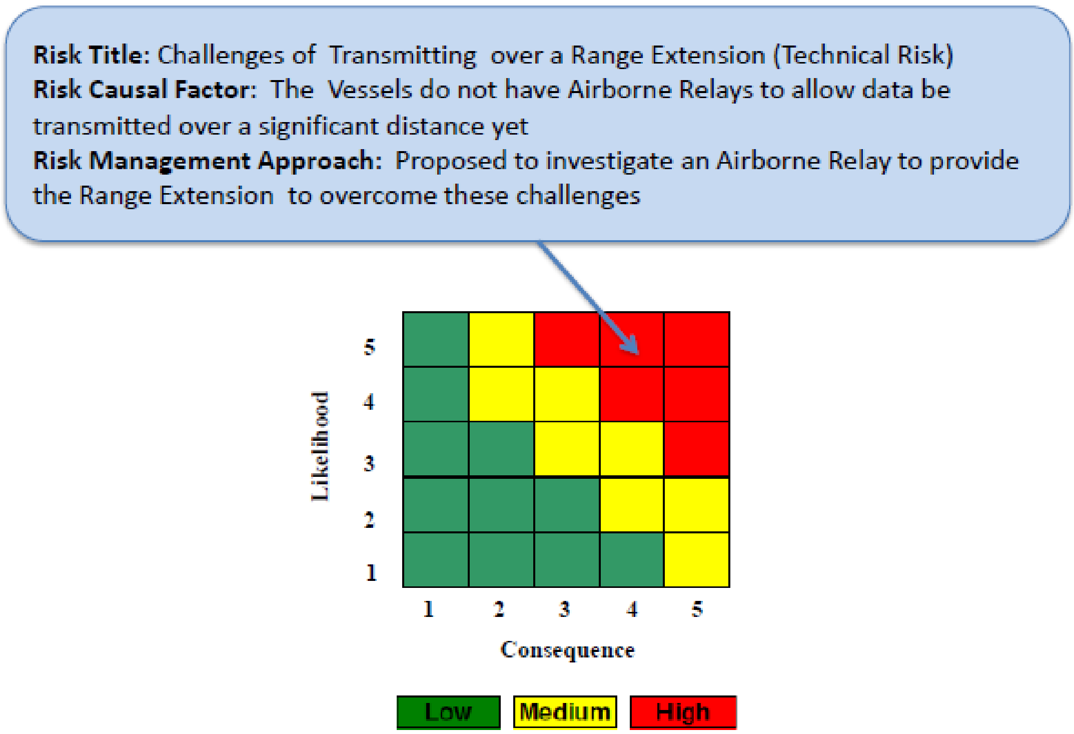

Figure 19 – Challenges of Transmitting over Range Extension Risk Matrix

5.2.6 Limitations of Applications of Wireless Technology

Mobile WiMAX (802.11e)and RF wireless communications technologies, in general, have inherent technology limitations with respect to range and effective data rates. A field test conducted by the Satellite Users Interference Reduction Group (SUIRG) with support from the U.S. Navy, the Global VSAT Forum, and several other member organizations yielded results that showed interference at 12 km when using the same communications channels for both the WiMAX systems and satellites in C-Band (3.40 GHz – 7.075 GHz). It was found that within this band, WiMAXcould not reliably deliver 70 Mbit/s of data at ranges over 50 kilometers (31 miles). Like all wireless technologies, WiMAXis able to operate at high bitrates for short distances, however, as range increases, bitrate must decrease. During experimentation, it was found that when operating at the maximum range of 50 km (31 miles) there were significant increases inthe bit error rate, providing a much lower effective bitrate. Conversely, by reducing the range (to under 1 km), the device can operate at much higher bitrates. Although this issue may become a performance factor for the ship-to-ship links in the future, the proposed design of our bandwidth sharing architecture should not be greatly affected by this limitation in technology. The research presented in this paper proposes that to increase the download capability of a disadvantaged user, the data link between the user and the ship with the excess communications bandwidth need only be greater that the excess bandwidth to be utilized (i.e. to gain access to 4 MB/s of satellite communications, the ship to ship link need only be a consistent 4 MB/s to alleviate data buffering). The data links being investigated provide significantly greater bandwidth (30 MB/s minimum). Therefore, the degraded link should still provide the minimum bandwidth required to allow optimum download rate. The likelihood of encountering this deficiency is near certain (5), and the consequences may provide a minor reduction in technical performance (2).

Mitigation:

As mentioned previously, the risk can be accepted as stated. However, possible mitigation techniques include investigation of other protocols to transfer the data and the use of other mediums such as Free Space Optical to communicate. Free Space Optical communications is discussed in the conclusions section of this paper.

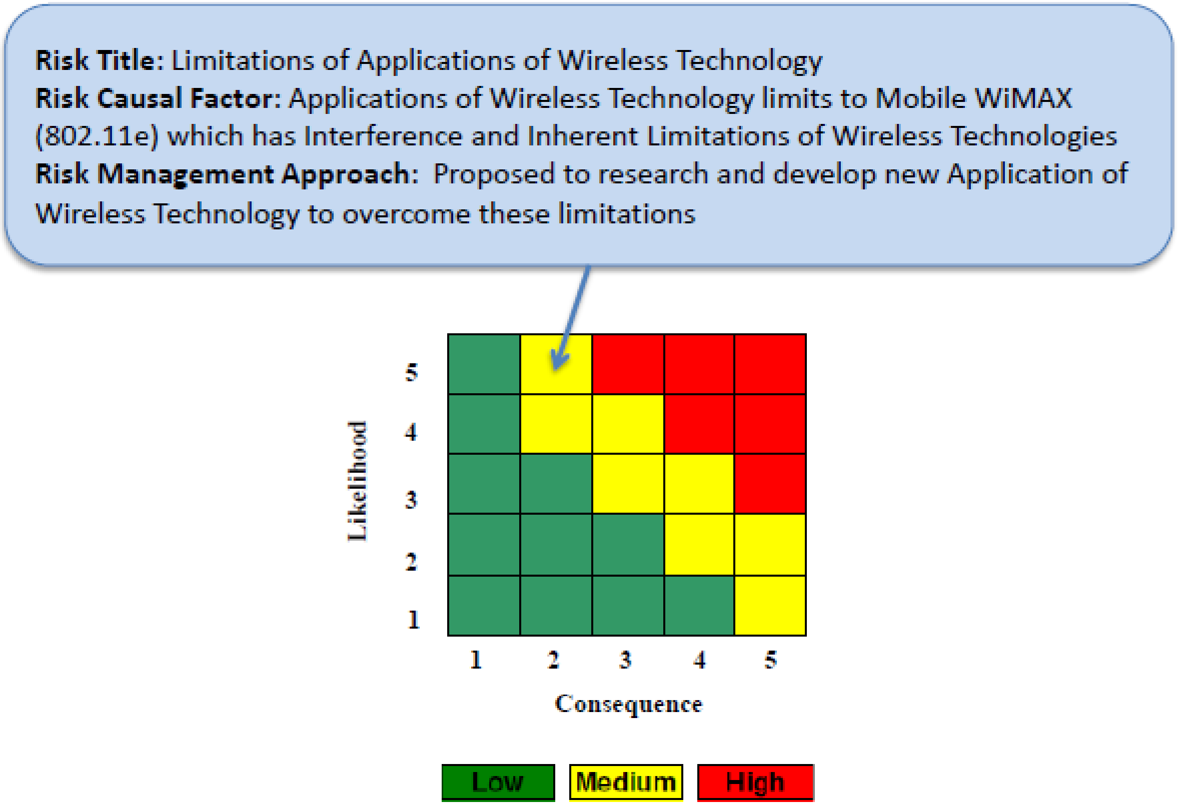

Figure 20 – Limitations of Applications of Wireless Technology Risk Matrix

5.2.7 Limitations of Hardware on US Navy Vessels

As alternative communications technology develops, space limitations become apparent when installing equipment onboard vessels. The location of additional antennas, either omni-directional, or directional requires significant planning to reduce the platform radar cross section or to eliminate interference with other equipment located near transmitting devices. In addition, hardware boxes for communications equipment require energy and space and reduce platform capacity. For the proposed system, the likelihood of encountering restrictions on locating equipment onboard a naval vessel is likely (3) and the consequences to performance are a minor reduction in technical performance (2).

Mitigation:

Although further research needs to be accomplished to determine needs and requirements for antennas and hardware for the proposed system,performing research on advanced antenna design using either novel configurations or meta-materials can increase the mitigation effort.

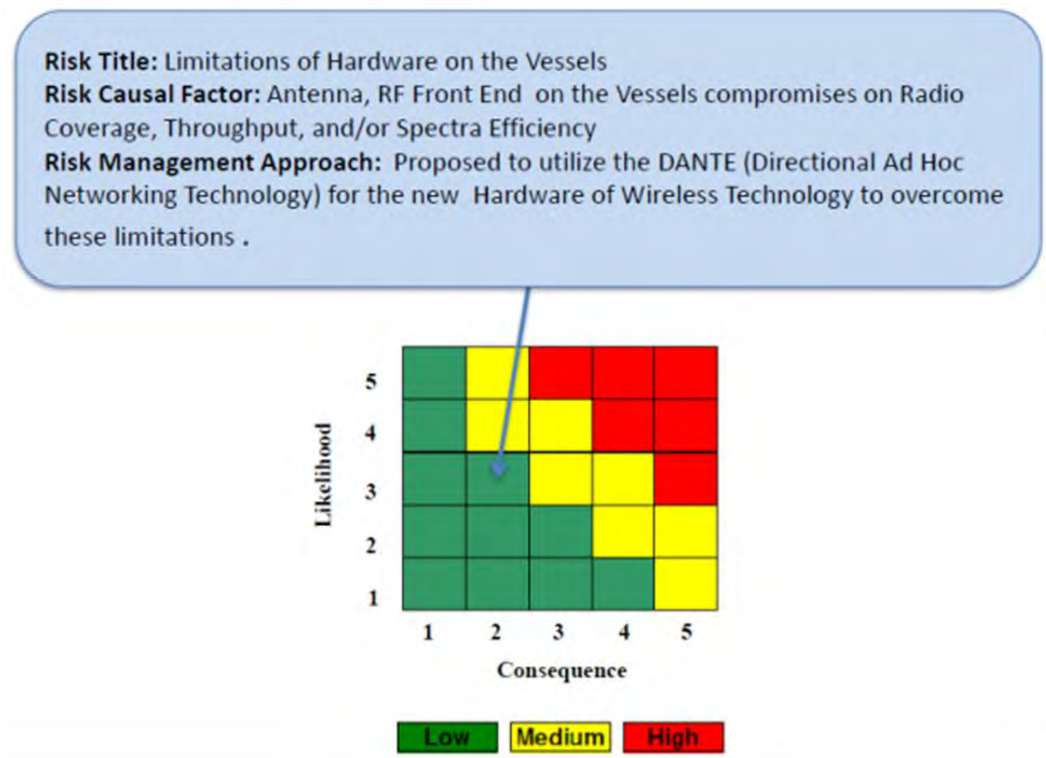

Figure 21 – Limitations of Hardware on US Navy Vessels Risk Matrix

5.2.8 Challenges of Mobile Wireless Network Software Risk and Mitigation Strategy

Mobile wireless network software posesmany challenges when operated in a dynamic environment. These challenges include the network topology and planning, self-organization and reorganization of the nodes within the topologies, traffic routing, traffic route planning, network protocols and flow control (the effect of the bit errors). The challenges of operating in the marine environment can compound data transmission difficulties, which may require additional protocols to be developed to minimize data delay under harsh environmental conditions. Methods need to be created to determine and establish optimum routes through a shared communications link as well as ensuring that the network remains as a self-organizing mesh. It is likely (3) that the system under development will need to consider additional capabilities to perform as designed, and the consequences of the lack of existing capabilities will result in significant degradation of technical performance (4).

Mitigation:

Perform requirements analysis to determine issues necessary to create reliable connectivity of nodes in the maritime environment. Develop and demonstrate capabilities to maintain connectivity during war-fighter exercises.

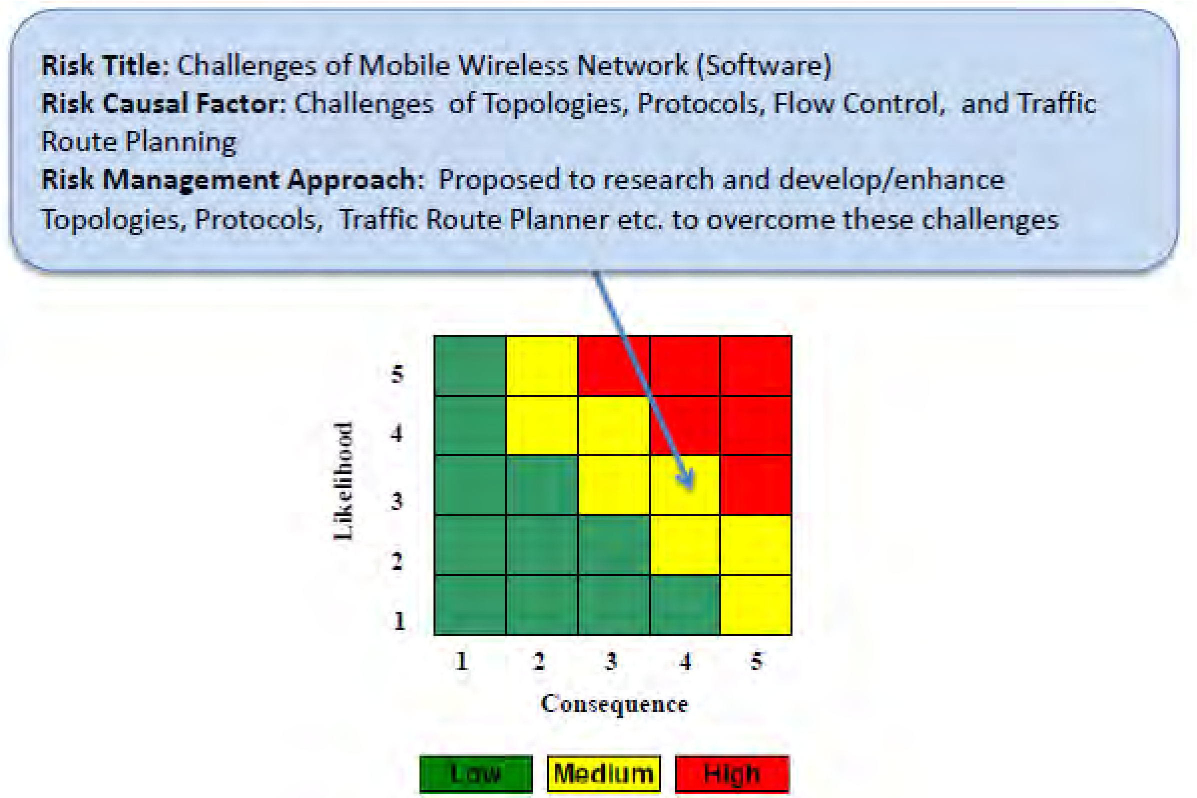

Figure 22 – Challenges of Mobile Wireless Network Risk Matrix

5.3 Risk Summary

Table 15 – Risk Analysis Results

Risk ID	Risk Factor	Like.	Cons.	Rating
1	Architecture: Naval Communication Architecture does not support the RFLOS	5	5	High
2	Policy: Large Vessels are reluctant to give up bandwidth to other Vessels	5	5	High
3	Technical Risk: Reliable High Bandwidth Communications between Vessels are difficult to achieve	3	3	Medium
4	Technical Risk. Satellite Communications: The Vessels do not have Download Managers	5	4	High
5	Technical Risk: Challenges of Transmitting over a Range Extension since the Vessels do not have Airborne Relays	5	4	High
6	Technology: Applications of Wireless Technology limits to Mobile WiMAX (802.11e)	5	2	Medium
7	Hardware: Antenna, RF Front End on the Vessels compromises on Radio Coverage, Throughput, and/or Spectra Efficiency	3	2	Low
8	Software: Challenges of Mobile Wireless Network including Topologies, Protocols, Flow Control, and Traffic Route Planning	3	4	Medium

The identified risks for the proposed operational design are measured as the combined effect of the probability of occurrence and the assessed consequence given the occurrence, ***Table 15***. The majority of the risk analysis performed is based on the potential of not meeting a specified benchmark. The investigation categorizes risk against those benchmarks whether they are architecture, policy, technical, technology, software, or hardware. This process was completed to quantify the potential loss or impact of each circumstance in the summary table.

The 8 items listed in ***Table 15*** were identified as the most significant risks associated with implementation of the bandwidth sharing architecture that would allow smaller ships access to high bandwidth data through a larger capacity communications link. Risks 1 and 2 are associated with U.S. Navy policies and risks 3 through 8 are technical in nature. High bandwidth LOS data communications at sea is a relatively new ability that was demonstrated as early as 2003 in the Trident Warrior Exercise by the Intra Battle Group Wireless Network (IBGWN). In the years since 2003, hardware and software solutions which address needed technologies have been provided in exercises and experiments, however, with the exception of a few communications links which show promise of helping with a solution, none of these experiments has yielded product that is ready for production or fielding. As a result, it is possible that some risks may require significant investment in time and expense to arrive at a solution that would provide necessary capability in all environmental conditions.

6 Summary and Conclusion

The research indicates that the current Naval communication architecture does not provide for disadvantaged users to benefit from resources available on the Global Information Grid (GIG). Small and medium sized ships have limited satellite communications bandwidth (256 - 512 Kbps), which prevents them from accessing large stores of data that could increase their situational awareness or mission effectiveness. Since data transfers from large data sets would impair the major communications link of the ship for the extended periods of time, the commanding officer of the ship would be reluctant to use the SATCOM link for access to the GIG. Subsequently, as information richness with the GIG increases, the access limitations to the disadvantaged user will remain a major challenge.

Table 16 is presented to illustrate the benefits of the proposed system.

Table 16 - Summary of Simulation Results

Metric	Throughput (Mbps)		Throughput Improvement		Transfer Time (minutes)		Transfer Time Improvement	
Packet Loss	0.1%	5%	0.1%	5%	0.1%	5%	0.1%	5%
Scenario 1	0.49	0.47			56.2	59.1		
Scenario 2	1.52	1.45	209%	209%	18.2	19.1	68%	68%
Scenario 3	3.94	3.74	699%	699%	7.0	7.4	87%	87%

The data in the table clearly demonstrates that by allowing small and medium sized ships access to a portion of the SATCOM bandwidth from the large ship will allow the disadvantaged ship expedient access to the Global Information Grid without significant disruption to the large ship. The table illustrates how a medium sized ship (LCS) accessing the GIG to obtain 200 MB of data for a mine clearance mission would be unable to utilize its SATCOM for any other purposes for almost an hour during receipt of the data from NAVOCEANO. In Scenario 2, the LCS would utilize a ship-to-ship link (DMR) to obtain the data by accessing 4 Mbps of a large deck ships (carrier or amphib) SATCOM link. The time for the LCS to obtain the data is reduced to less than 20 minutes, and during the download of data from NAVO, the ship is able to utilize all 512 Mbps of throughput available through its own SATCOM. In Scenario 3, the ship-to-ship link is accomplished through a WiMax connection, reducing the amount of time necessary to retrieve data to less than 8 minutes. This scenario provides the LCS with an extremely fast method to obtain information required to optimize their MCM planning tool without degrading their primary means of communicating with the external world.

It was found that small and medium sized ships, performing operations within a Carrier or Expeditionary strike group, can benefit by utilizing excess SATCOM bandwidth that is available on large ships. The larger ships within the strike group have a much greater communications bandwidth capacity (4 – 8 Mbps) and may be able to provide some of this bandwidth to the disadvantage user. The bandwidth sharing between the ships would greatly reduce the duration of the data transfer, providing the disadvantaged user the ability to benefit from the GIG resources without disabling their own ships communications link for extended periods of time. This capability can be created by establishing a high bandwidth digital data link, (mesh network), from ship-to-ship, through which the GIG data would be passed.

Using this construct would create the communications path through which data could be relayed through the large ship. The research demonstrated that a medium sized ship utilizing only one half of the large ships available bandwidth could improve the delivery time of critical data by 87% over the amount of that would be required if it used its own satellite link.

The risk analysis conducted during research indicated that there are significant challenges, which must be overcome in order to adopt the proposed architecture. The risk analysis table identified 8 hurdles that must be addressed during implementation of this architecture.

Table 17 - Risk Analysis Results

Risk ID	Risk Factor	Like.	Cons.	Rating
1	Architecture: Naval Communication Architecture does not support the RFLOS	5	5	High
2	Policy: Large Vessels are reluctant to give up bandwidth to other Vessels	5	5	High
3	Technical Risk: Reliable High Bandwidth Communications between Vessels are difficult to achieve	3	3	Medium
4	Technical Risk. Satellite Communications: The Vessels do not have Download Managers	5	4	High
5	Technical Risk: Challenges of Transmitting over a Range Extension since the Vessels do not have Airborne Relays	5	4	High
6	Technology: Applications of Wireless Technology limits to Mobile WiMAX (802.11e)	5	2	Medium
7	Hardware: Antenna, RF Front End on the Vessels compromises on Radio Coverage, Throughput, and/or Spectra Efficiency	3	2	Low
8	Software: Challenges of Mobile Wireless Network including Topologies, Protocols, Flow Control, and Traffic Route Planning	3	4	Medium

In order to initiate development of the proposed architecture, it will be necessary for communications policies to change which will allow smaller ships to access portions of more capable SATCOM links. Without this ability, the disadvantaged user will be limited to the minimal bandwidth that is installed on their ship.

The ship-to ship communications links will need to be augmented to provide links beyond the 12 – 15 mile limits which currently exist in the absence of airborne relays. The limited range that currently exists would restrict disadvantaged users from access to the GIG unless they were transiting in tight formation. This would cause additional vulnerability to the strike group while in formation.

Hardware and software need to be developed which will not be affected during operation in the harsh maritime environment. The higher frequency communications links which are required to pass high bandwidth data links are very susceptible to degradation in performance in mist, fog or rain. Methods to increase performance during inclement conditions must be developed to provide reliable ship-to-ship links.

7 Recommendations and Areas for Further Research

It is recommended that an investigation of existing communications architecture and policies should be conducted. The investigation should be focused on determining issues that need to be addressed that would allow communications bandwidth sharing between ships.

Experimentation, and research, should be continue on developing high bandwidth data links and mesh networks for Naval communications, with particular emphasis on overcoming technical issues associated with marine related environmental conditions. Additionally, methods to extend the range of these networks beyond line of sight using communications relays should be improved.

Research on algorithms that would dynamically determine the most effective communications path within a strike group should be conducted. The system would query available SATCOM links to determine user load and create the optimal link to share information.

Finally, an investigation of these issues and benefits of installing download managers in all SATCOM terminals should be conducted. The research would help to determine performance issues that may be encountered due to the additional overhead required by the download manager.

APPENDIX A: Acronyms and Definitions

16APSK - 16 Any Amplitude and Phase Shift Keying

8PSK - 8 Phase Shift Keying

ADNS - Automated Digital Network System

BCH - Bose Chadhuri Hochquenghem

BLOS - Beyond-Line-Of-Sight

C4I - Command, Control, Communications, Computers, and Intelligence

CANES - Consolidated Afloat Network Enterprise System

CENTRIXS - Combined Enterprise Regional Information Exchange System

CONOPS - Concept of Operations

COTS - Commercial off the Shelf

DANTE - Directional Adhoc Networking Technology

DIACAP - DoD Information Assuarance Certification and Accredidation Process

DISA - Defense Information Systems Agency

DoD - Department of Defense

DVB-S2 - Digital Video Broadcasting Series 2

EIRP - Effective Isotropic Radiated Power

FSO - Free Space Optics

GIG - Global Information Grid

GOTS - Government Off the Shelf

IP - Internet Protocol

IPE - Intelligence Preparation of the Environment

LCS - Littoral Combat Ship

LDPC FEC - Low Density Parity Check Forward Error Correction

LOS - Line of Sight

LPD - Low Probability of Detection

LPI - Low Probability of Interception

MB - Megabtyes

MEDAL EA - Mine Warfare Environmental Decision Aid Library Enterprise Architecture

MRR - Modulating Retroreflector

NAVO - Naval Oceanographic Observatory

NAVOCEANO - Naval Oceanographic Observatory

NCA - Naval Communication Architecture

NCES - Net-centric Enterprise Services

NSA - National Security Agency

OFDM - Orthogonal Frequency Division Multiplexing

ONR - Office of Naval Research

OPNAV - Office of the Chief of Naval Operations

PEO - Program Executive Office

PEO-LCS - Program Executive Office for the Littoral Combat Ship

PMW -Program Manager, Warfare

QPSK - Quadrature Phase Shift Keying

RF - Radio Frequency

RFLOS - Radio Frequency Line of Sight

SATCOM - Satellite Communications

SBA - Service Based Architecture

SPAWAR - Space and Naval Warfare

SPAWN - Spatially Aware Wireless Network

SUIRG - Satellite Users Interface Reduction Group

TDA - Tactical Decision Aid

TREC - Tactical Reachback Extended Communications

UAVs - Unmanned Aerial Vehicles

US - United States

APPENDIX B: Technology Readiness Levels

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins with to be translated into applied research and development. Example might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in a operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and 'flight qualified' through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system 'flight proven' through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

APPENDIX C: Candidate High Bandwidth Data Carriers

I. SeaLancet™ (RT-1944/U) Network Radio (Multi-Band Networked Radio)

The SeaLancet™ (RT-1944/U) radio is a compact, lightweight radio developed to provide high bandwidth communications in any operational environment. This radio could work well in conjunction with the recommended DANTE solution because DANTE supports tactical radios. The RT-1944 provides wireless WLAN network services for both line-of-sight (LOS) and beyond-line-of-sight (BLOS). It uses full TCP/IP routing and supports FORCEnet and NetCentric operations so this lowers the risk to deployment for the fleet.

The RT-1944/U uses Orthogonal Frequency Division Multiplexing (OFDM) to help minimize effects of multi-path conditions introduced in complex environments. The radio operates in the following frequency bands:

- Band 1: MIL 220 to 2400 MHz in 5 MHz steps, utilizing 37 overlapped channels and 10 non-overlapped channels
- Band 2: MIL 4800 to 5000 MHz in 5 MHz steps, utilizing 37 overlapped channels and 10 non-overlapped channels
- Band 3: ISM 2400 to 2500 MHz in 5 MHz steps, utilizing 17 overlapped channels and 5 non-overlapped channels
- Band 4: ISM 5000 to 5900 MHz in 5 MHz steps, utilizing 177 overlapped channels and 45 non-overlapped channels

Figure C.1 - SeaLancet™ Radio

The compact unit weighs less than 8 pounds including the amplifier so minimal ship space is required for use that reduces risk. Other characteristics of the radio that would contribute to the success of the Next Generation Automated Digital Network System (ADNS) concept include:

- High throughput links—up to 54Mbps link rate (32Mbps user data throughput), adaptable 108Mbps link rate (high-capacity point-to-point)
- Long range, extending LOS beyond 150 miles (and OTH with relay)
- Robust link using an enhanced OFDM waveform
- Military and ISM frequency, multiband operation
- Supports IP traffic of all types, including video, file transfer, IP, chat, email, and sensor data
- NSA Type-1 encryption capable (SecNet® KIV-54)
- Can be combined with multiple omni and directional antenna configurations (built-in antenna control)
- Supports IPv4/v6 protocols

- Two modes: Point to Multipoint high capacity IP-based data link and MESH/Adhoc networking

The user realized data throughput, excluding all headers, trailers, error correction, etc, for a 54 Mbps link burst rate, is greater than 30 Mbps. This performance would also allow disadvantaged platforms (medium and small deck ships) to benefit from future increases in satellite communications bandwidth, which will be realized on the large deck ships, and could provide the ability for units transiting within a strike group to create a mini-cloud network environment. Additionally, the radio can be configured to incorporate NSA Type-1 encryption. Another capability that this radio provides is that multiple antenna types and configurations can be controlled by software built into the radio. This feature could be used to provide optimized antenna configuration during operations.

The ability for ships to communicate Beyond Line of Sight (BLOS) is a critical need for adopting a system that allows external communications links to be shared. The compact size of the SeaLancet™ would allow it to be carried aboard small Unmanned Aerial Vehicles (UAVs) or aerostats. The increase in altitude for one link of the communications path would extend the range significantly. During testing, single hop ranges over 100 nautical miles have been realized.

Free space optics is a current commercial technology that is already deployed and it provides wireless bi-directional HD and SD-SDI video transmission with no compression and no delay (Free Space Optics, 2011). It operates at 1.5 Gbps and transmits HD/SD video, audio, and control signals bi-directionally without delay via LOS but the distance is rather limited to about 1km so this may not be a good solution for the fleet but if the technology progresses it could be worth researching further.

II. Tactical Reachback Extended Communications

The Tactical Reachback Extended Communications (TREC) system is a compact, high bandwidth data link that operates in the frequency range between 37.0 and 38.2 GHz. The unit is designed to be mounted on a group three or higher unmanned aerial vehicle to extend the data link to ranges up to 130 km at 150 Mbps. During testing, the throughput was 300 Mbps at 93 km and 720 Mbps at 56 km. Again, this link is dependent on a method to place the relay at altitude; however, the high bandwidth and extended range will ensure that AADNS functionality would be available.

The TREC radio utilizes a Digital Video Broadcasting- Series 2 (DVB-S2) standard waveform, which allows encoding using any of these techniques:

- Quadrature Phase Shift Keying (QPSK)
- 8 Phase Shift Keying (8PSK)
- 16 Any Amplitude and Phase Shift Keying (16 APSK)
- Bose-Chadhuri-Hochquenghem/Low Density Parity Check Forward Error Correction (BCH/LDPC FEC)

These techniques provide great flexibility for performance in different operating environments. The radio automatically adapts symbol rate, modulation, code rate and power to link conditions and quality of service requirements. During testing the system provided 300 Mbps performance using 8PSK ¾. Additional characteristics include software defined radio compatibility, weather resistant design and fully environmentally qualified.

A diagram of the major components and design characteristics for the TREC radio is shown in ***Figure C.2***.

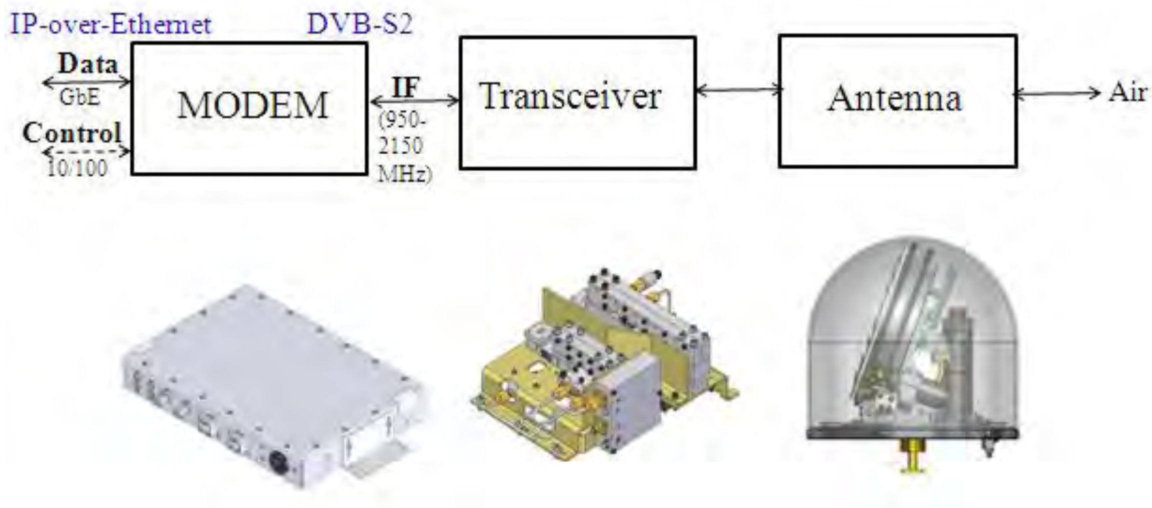

Figure C.2 - TREC Radio Major Components

It is projected that the overall weight of the aerial relay node will be less than 11 pounds. By incorporating this technology into the Concept of Operations (CONOPS) developed for CSG/ESG, the Navy could realize significant benefits by providing additional bandwidth to disadvantaged users. The 150 Mbps of data throughput would allow the small and medium deck ships to ―borrow" bandwidth from the large deck ships while providing connectivity for other functions that may require a high data rate communications link.

III. Free Space Optics

A novel solution to provide a high bandwidth, networked link between platforms is being pursued by the Office of Naval Research. Advances in electronics and processing techniques in the past few years have created a system that is near ready for implementation. The technology known as Free Space Optical (FSO) communicationsisa networked communications link that provides data throughputs, which can range from 100 Mbps to 1 Gbps in favorable conditions.

FSO communications can be conducted in one of two modes. The first mode to be described is Bidirectional FSO, shown in ***Figure C.3***, where both end of the communications link have an amplified laser source that sends digitized data from a host to a designated receiver.

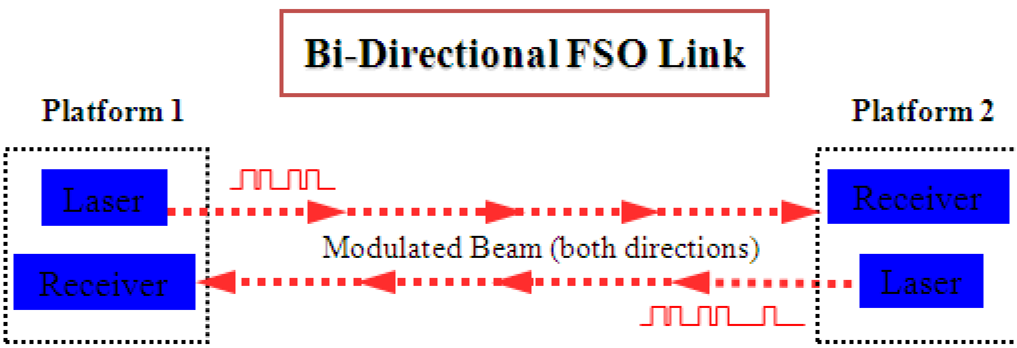

Figure C.3 - Bi-Directional FSO Link

The major benefit of the bi-directional configuration is the creation of a full duplex communications link which allows continuous transfer of two way information, the downside being that both ends of the link need to contain both a laser transmitter and an optical receiver. This configuration increases power requirements as well as increasing system cost. The second type of FSO communications is known as Modulating Retroreflector (MRR) mode. In this configuration, a source laser transmits a beam to an optical receiver which receives the source signal and inserts a modulated component onto the input signal which is then reflected back to a receiver where it is decoded to obtain the communications data, as shown in ***Figure C.4***.

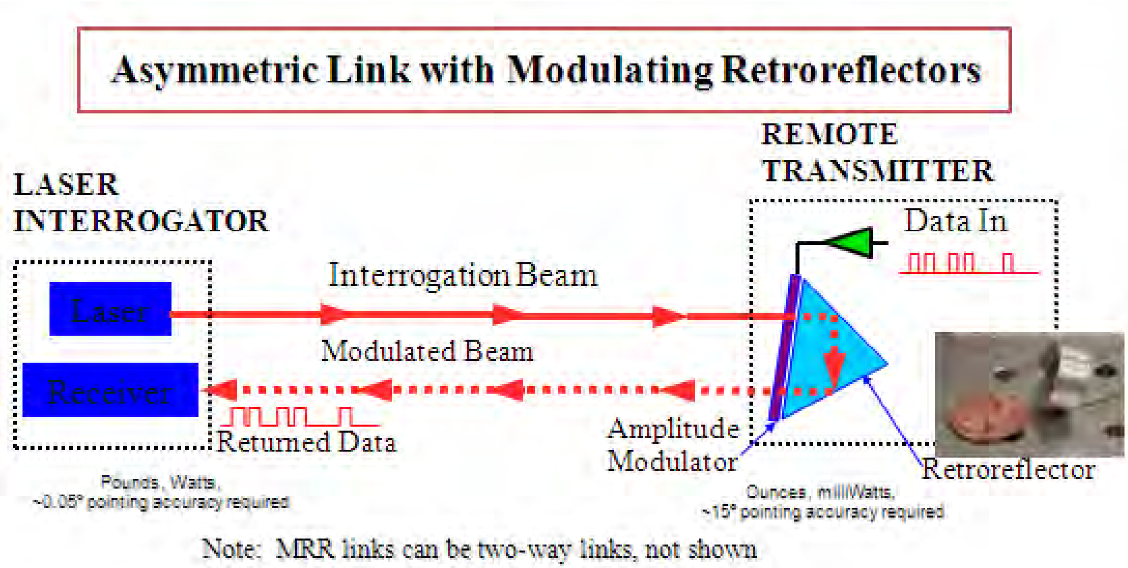

Figure C.4 - Asymmetric FSO Link with MRR

ONR 312 Provided Image with Retroreflector

The figure shown illustrates a unidirectional link; FSO with MRR can also be configured as a bi-directional link by including a source and receiving mirror on both ends of the link. Unidirectional mode reduces size, weight and complexity of one side of the link by eliminating the additional laser source.

A comparison chart that provides benefits of laser-based communications against radio frequency based communications is shown in ***Table C.1***.

Table C.1 - FSO vs. RF Communications

Lasercomm advantages over RF:	RF advantages over lasercomm:

• Jam Resistant:
  • Jammer must be within LOS and inside the narrow field of view of the receiver
• Low Probability of Intercept and Detection:
  • Beam diameters < 0.05 degrees
• Currently no frequency spectrum approvals:
  • System operates at ~193,500GHz
  • No permission issues in international ports
• No EMI or RF Interference problems:
  • Systems may be installed within feet of eachother
• High data rates are readily achievable:
  • Systems leverage fiber telecom components at Ethernet and Gbps rates
• Small size, weight, and electrical power
  • RF systems need power amplifiers (and cooling) to close links over long ranges
• Operate during EMCON and HERO
• No multi-path interference issues
  • Beams propagate well in maritime environments and over flat terrain
	• Propagates through fog and clouds
	  • EHF (mmW) systems susceptible to rain fades
	• Propagates with few dropouts to atmospheric turbulence (scintillation)
	• Relaxes pointing tolerances
	  • LOS CDL beams are 3 degrees
	• Comms users are familiar with RF
	• Non-LOS communications are possible
	• Omnidirectional antennas are available

FSO is intended to augment existing RF system capabilities	

As shown in the table, there are many real advantages to the implementation of this technology as a ship-to-ship link to allow smaller ships to benefit from larger ships bandwidth. The primary advantage would be the availability of bandwidth under ideal conditions of 1 Gbps. This large amount of bandwidth would ensure that the link between the ships was always significantly larger than the satellite throughput being borrowed from the large deck ship, eliminating any potential communications bottlenecks. The large amount of reserve capacity supplied by the FSO link would also eliminate the need to seek other means of maintaining ship to ship connectivity as upgrades to satellite communications links create more bandwidth which could be shared. The Low Probability of Interception (LPI) and Low Probability of Detection (LPD) and anti-jam characteristics would allow information to be reliably transmitted in challenging tactical environments. Finally, since the communications link is based on light, there are no RF spectrum issues to contend with. This would provide operational capability worldwide with no political ramifications.

The major weakness in Free Space Optical communications is susceptibility to performance issues occurring in periods of limited visibility. The communications link is diffused when it is passed through dense media such as clouds, fog, rain, dust, smoke and other conditions where visibility is reduced. During these conditions, available bandwidth can be significantly reduced or eliminated completely. To ensure a continuous communications link in all conditions a redundant radio frequency based system would have to be installed. This RF link would be energized during periods of limited visibility and eliminated when the FSO link was re-established.

It is projected that FSO can be utilized to create communications links with ranges from 16 to 23 kilometers (km) when installed on 50 foot towers, and from 30 to 60 km when installed on 100 foot towers. It is likely that these ranges are insufficient to ensure S2S communications within an operational battlegroup consistently. However, it is possible using FSO with modulating retroreflector technology to extend the range with an airborne relay. The small footprint of the MRR would allow it to be installed on either unmanned air vehicles or aerostats to increase the range between ships up to 130 km.

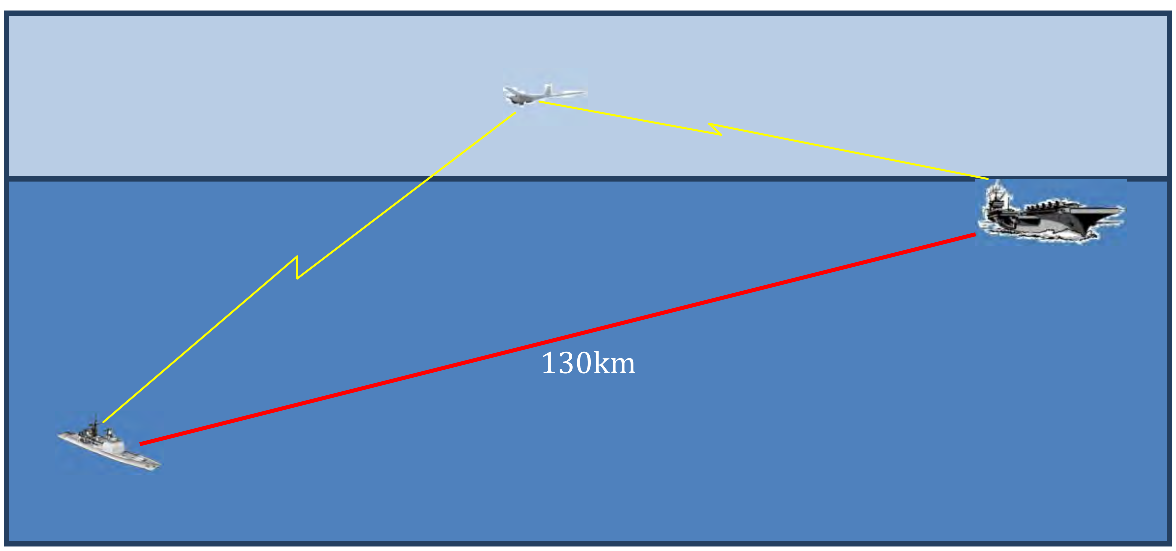

Figure C.5 - FSO Predicted Range with Aerial Relay

In summary, the use of a FSO link could be used to provide the link between ships to create the ability for a small unit to benefit from the larger units satellite communications relay. The system characteristics would not only provide ample bandwidth, which would ensure future compatibility, but could be used during periods of active jamming while allowing communications with a low LPI/LPD.

APPENDIX D: References

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